REPORTS OF THE SWEDISH DEEP-SEA EXPEDITION. VOL. III
PHYSICS AND CHEMISTRY. NO. 1

OPTICAL STUDIES OF OCEAN WATERS

BY

N. G. JERLOV

v.3

Contents

	Page
Introduction	3
Historical Survey	4
Stations	6
Submarine Daylight	9
Ultra-violet Radiation	30
Angular Distribution of Submarine Daylight	35
Colour of Ocean Waters	43
Transparency of Ocean Waters	46
Classification of Sea Waters	50
Total Radiation in the Sea	52
Summary of Principal Results	54
References	57

Introduction

Owing to the supreme importance of submarine daylight for maintaining marine life attempts were early made to get quantitative data on the subject. Since 1930 Swedish oceanographers have participated in this work under the guidance of HANS PETTERSSON. Modern methods have been elaborated and suitable instruments devised at Bornö Station for the purpose of studying subsurface radiant energy and the transparency of the sea. The results gained by these experiments in the sea are limited to the Skagerrak, the Kattegatt, and the Baltic, where the water containing more or less dissolved matter shows great variations in optical conditions.

Considering the experience gained it was a very attractive scheme to extend it to the oceans, though the methods had to some degree to be modified in order to meet the requirements of the clear ocean water. In other words, the Swedish Deep-sea Expedition was bound to take the opportunity of closely studying the optics of the oceans. In the program this meant a deviation from the main lines of the expedition, which was not to deal with the upper strata of the oceans but was devoted to the exploration of the ocean floor and the processes enacted close to it.

In fact, the oceans presented a rich field for research on the penetration of radiant energy, as the results so far reported on this subject were very few. The planned work aimed in the first place at studying light as far down in the sea as was possible with the photoelectric method. But it must be emphasized that the daylight measurements were not intended to cover a general survey of the transparency of the water of different areas. Such observations are always limited by the weather conditions; practically constant daylight above the sea is required, and in view of the difficult technique it is of no use trying to take measurements when conditions are not favourable. On the other hand, every water sample collected during the hydrographical work was to be studied in a Tyndall apparatus as to its amount of particles. Suspended particles are from an optical point of view the most interesting component in the sea and one that stands in a certain relation to the transparency. The results on particle distribu-

tion will be published later. The object of this paper is to report measurements of submarine daylight and transparency of ocean water as carried out by means of photo-electric methods *in situ*. They were confined to the uppermost 200 m. The daylight in deeper strata will be separately treated.

In the study of the subsurface radiation much attention must be paid to the biologically important short-wave part of the spectrum. Especially for penetration of the antirachitic ultra-violet in clear water, accurate measurements were highly needed. Thus it was planned to get data about this radiation as well by means of a special technique, if possible in off-shore waters.

The daylight in the sea is distributed over different angles owing to the direction of refracted sun-rays, the scattering, etc. This question, which was subjected to an earlier Swedish investigation by the present author and LILJEQUIST (1938), was taken up again because there remained some problems unsolved. One of these concerns the distribution in a very clear water and the mean path length to be applied here in order to reduce measurements made at different solar altitudes to the same standard. Another problem is the limiting angular distribution that is approached with increasing depth.

The method of measuring *in situ* the transparency of sea water to electric light by means of a selenium rectifier cell is very useful in the heterogeneous coastal waters. But the transparency-meter is not expected to be the proper instrument for recording the high ocean transparency, which shows vertically and horizontally small variations. It was not considered worth while to devise for the deep-sea expedition a new and more sensitive type of transparency-meter by increasing the light-way in the water. Nor could the technical difficulties be settled in due time by providing the meter with an ultra-violet lamp. In spite of these objections transparency measurements were not totally abandoned. The obje view was to obtain some transparency se in order to get the true transmission of water to different colours.

Historical Survey

The first measurements of subsurface tion date back to 1885 when FOL and SA made exposures of photographic plat different depths in the Mediterranean of d'Azur. Here, they found faint residual da still present at 400 m depth. In 1911 B photographed in the same area the da spectrum with the aid of a spectrograp determined how far down the different lengths gave a blackening of the An accurate spectro-photographical m though with low sensitivity, giving a qu tive spectral analysis of the light at ever was elaborated by KNUDSEN (1922).

The introduction of photo-electric c SHELFORD and GAIL (1922) for the st subsurface light implied a new step evolution of the technique. Emissio requiring an external source of E. M. F soon passed over by the selenium rectifi The use of selenium for recording light water dates back to 1889, when RI (1891) made some observations in the at Monaco. Much later the method was to observations at sea particularly t pioneer work of ATKINS and POOLE During the first few years of the 1930 TERSSON and LANDBERG (1934), UTT and BOYLE (1933), and CLARKE (1933) uted effectively to the progress of ou ledge of light penetration in different by using the selenium rectifier type holds its superiority to other instrum measurements in the upper strata bec its simplicity and sensitivity, though complications are involved in its use, stance the curvature error. In deep where a very sensitive device is essent

to fall back on photographic methods. udy the penetration of radiation in shal- nd calm water it may sometimes be con- nt to use a thermopile with colour filters, s firstly done by BIRGE and JUDAY (1929). e available material from oceans comprises some measurements by UTTERBACK (1936) e North Pacific Ocean near the coast of ington, and the observations by OSTER and KE (1935) and by CLARKE in the Mid tic and in the West Atlantic (1936). These s will later be taken up for discussion. may be added that the theoretical side of problem is treated among others by LE D (1939) and by LAUSCHER (1947) under assumption of uniform scattering and for water.

e experimental data for the penetration tra-violet in sea water are also few. It evant to make a review of them. On the of laboratory measurements HULBURT 3) and SAWYER (1931) found a fairly high of absorption for ultra-violet by sea water. at 360 mμ their extinction values exceed per m. The work by DARBY, JOHNSON BARNES (1937) near the Tortugas Labora- suggests that sea water is much more sparent to ultra-violet than was previously posed, but these authors have only given ive values. CLARKE and JAMES (1939) d that »pure» sea water measured in a ochromator after Berkefeld filtering ex- ts a transparency of about 95 % per m at mμ. The corresponding value for double- lled water is 95.5—96.4 % according to careful work of JAMES and BIRGE (1938). lently, accurate values for the absorption nti-rachitic radiation by sea water are ing, but TSUKAMOTO (1928) has observed a heavy absorption by water does not in until at 230 mμ.

1 1937 the problem of the angular distribu- of daylight in the sea was taken up by LOV and LILJEQUIST (1938). They used a tometer which receives a narrow cone of light and which is adjustable in any direction. Their measurements afford complete polar diagrams of the illumination at the actual depth. Below the surface, maximum intensity is in the direction of refracted sunrays. With increase of depth the curves grow relatively in breadth, and the vertical intensity is increased. These features have been confirmed by WHITNEY (1941). In some cases there is a slight reduction in obliquity of the major axis of their curves.

With the aid of a cubical photometer ATKINS and POOLE (1940) compared the downward, upward, and horizontal illuminations. On the basis of these results POOLE (1945) interpreted the limiting angular distribution pattern that is approached in deep water. According to him, the constancy of the ratio horizontal/vertical light indicates that the average obliquity tends to a constant value governed by a balance between the opposing effects of absorption and scattering, one decreasing and the other increasing the obliquity with increase of depth.

The ratio of the upward to the downward illumination is determined at various localities. UTTERBACK (1936) found 1—1.5 % for green and 1.9—2.2 for blue in the waters of San Juan Archipelago. In deep water in the Gulf of Maine, CLARKE (1936) obtained for green 2.5 % while ATKINS and POOLE (1936) report 2 % and 0.5 % for high and low sun altitudes respectively in the English Channel. JERLOV (1946) has shown that the ratio for Swedish areas is subject to wide variations but that values of 2 % for green and of 1 % for blue light at high solar altitudes are very probable.

The character of the upward travelling light is intimately connected with the colour ot the sea. The colour of the sea has been roughly determined by comparing the colour of the submerged Secchi disc with the »Forel scale». Such measurements have been made in all areas of the Atlantic and in the Mediterranean (see SCHOTT, 1926). By field observations made with the use of a special device, by laboratory

experiments, and by theoretical deliberations KALLE (1938) has critically examined existing theories concerning the colour of the sea. According to him, the intense blue colour of the clearest ocean waters is attributed to selective scattering. The shift of the colour to green in turbid waters is due to »yellow substance». Originating from carbo-hydrates in mainly phytoplankton and related to fulvic acids this substance is contained in sea water as a soluble and stable product of yellow colour. It is always accompanied by a substance exhibiting fluorescence, but this seems to be of minor importance from an optical point of view.

The daylight in the water is distributed over different angles, most of the light below the surface being concentrated round the direction of refracted sunrays. Therefore the measured extinction coefficient per m depth or the »vertical extinction coefficient» is valid for a mean path length, *i. e.* the mean value of the path lengths that light quanta must travel in order to descend one m in depth. The mean path length, which is consequently always above 1 m, is theoretically considered by WHITNEY (1938 a) under simplifying assumptions, *e. g.* uniform sky and no scattering in the water. From the measurements by JERLOV and LILJEQUIST values of the mean path length for coastal waters may be derived, as will be shown later. Being dependent on the solar altitude at the measurement the mean path length may be used for converting transmissions per m depth into the same standard of solar altitude. The conversion involves as a rule minor corrections.

As regards the transparency of the sea, it may in the first place be referred to observations by means of the Secchi disc. This method, which gives a rough picture of the transparency in the surface layers, has been widely employed in various areas. A physically more satisfactory method was introduced by HANS PETTERSSON in 1934. This measures *in situ* the transparency of sea water to electric lig means of a selenium rectifier cell. Tra ency-meters built on this principle hav used in coastal waters (PETTERSSON, WATTENBERG, 1938; WHITNEY, 1938; Y 1939; LILJEQUIST, 1940; JOSEPH, 1949; FINGTON, CARSOLA and DIETZ, 1950) an in lakes (SAUBERER, 1938; ÅBERG and R 1942), and they present an effective me tracing the presence of organisms in the Recently, JOSEPH (1950) has shown t some cases the transparency is a me characterizing the water. When standa (JERLOV, 1944), the transparency-meter the true extinction or the sum of abso and scattering, whereas the daylight meter records the sum of absorption part of the scattering. The transparency is easily provided with an arrangeme introducing colour filters automatica front of the lamp in order to obtain the parency to different spectral regions. been pointed out that in preference to a atory method, with which the laborio lecting of water samples reduces the n of tests of the extinction, the direct m of measuring *in situ* has the advantage allows a study to be made of the cont alteration of the transparency with dep thus enables microstratification, which even in off-shore waters, to be detecte the other hand, a laboratory method ploved by JAMES and BIRGE (1938) a CLARKE and JAMES (1939) by filterir water sample, offers the possibility tinguishing between the extinction d particles and that due to dissolved m This procedure is, however, too labori be used conveniently in routine work

Stations

Usually the field work is not in full conf with the plan drawn up. The experience is applied to modify the course of wo

ographic research the weather is always a
g factor for the progress of observations.
pertinent to give a rapid survey of meas-
nts of submarine daylight and trans-
y carried out during the Swedish Deep-
xpedition and to present a list of the
s concerned.

ing the first cruise in the Atlantic there
o time left for other than the most
tant core-sampling. In the Carribean
station 29) the arrangements designed for
measurements were tested for the first
during the expedition and found to
on for their purpose. Here, the spectral
meter as well as the transparency-meter
owered down to 50 m.

er Panama a transparency section was
but could not be fulfilled because of
le with the 600 m rubber cable, which
d some leakage. After repairing the
ge some stations were taken up near
Galapagos. Later, on the route Tahiti-
ii a transparency section including
stations was made across the equatorial
nts.

Pacific, especially the eastern part, did
how favourable daylight conditions, as
often clouds before the sun caused the
ght to vary considerably. When oppor-
es arose, measurements were carried out
e visible region or at least for the blue.
t must be admitted that because of the
se hydrographical work undertaken when
equatorial currents were being crossed
was not always time enough for light
vations in the upper strata.

order to obtain calm conditions the
attempt to study the anti-rachitic ultra-
radiation was made from a small boat
e Kapingamarangi atoll. The result was
ling, as the transmission values found
much higher than earlier results from
atory measurements and from investiga-
in coastal waters. The first test was
tedly verified in January and February, 1948, by measurements in the West Pacific Ocean and in the Indonesia Seas.

The Indian Ocean in March and April before the monsoon presented day after day ideal weather with a smooth sea and a cloudless sky, so that here most problems connected with the submarine daylight could be attacked.

Similar favourable conditions were also found in the Mediterranean, where visible daylight and ultra-violet were studied, particularly in the extremely clear water in the eastern part. As experiments in the Mediterranean are not disturbed by ocean swell, attempts were made with instruments designed for investigating the angular distribution of daylight. The device when at 100 m depth was found to be affected by currents and by the drift of the ship, so that the adjusted vertical angles did not hold true. These measurements were therefore confined to the surface layers.

In the continued work in the Atlantic all opportunities for observation were taken. Special regard was paid to daylight and transparency at the Romanche Deep and in the Sargasso Sea. In the latter area, characterized by maximum clarity for natural waters and by an intense blue colour, directional experiments were also conducted.

Data having reference to the stations are collected in Table 1. For the state of the sea the four first symbols of the Douglas sea scale are used:

0 Calm
1 Smooth
2 Slight
3 Moderate

The swell is expressed according to the »Meteor»:

0 Calm or small
1 Moderate
2 High
3 Long and flat
4 Irregular

TABLE 1. Station list.

Station	Position	Date	Wind m/s	Sea	Swell	Clouds	Measure
		1947					
29	N 14° 54′, W 63° 55′	13 VIII	3	1	0	cloudless	T I
46	N 04° 41′, W 82° 25′	30 VIII	2	1	1	—	T
53	S 02° 53′, W 90° 25′	7 IX	6	2	3	—	T
101	S 15° 57′, W 148° 57′	23 X	4	2	1	acu, cist 2	B
107	S 03° 21′, W 153° 36′	12 XI	10	4	1	—	T
108	S 02° 01′, W 152° 16′	13 XI	5	2	1	cloudless	L
111	N 00° 02′, W 151° 07′	15 XI	13	3	1	—	T
117	N 07° 37′, W 148° 58′	19 XI	3	1	4	—	T
123	N 15° 14′, W 152° 49′	25 XI	8	3	1	—	T
141	S 02° 50′, E 171° 18′	31 XII	2	1	0	cu 5	BU
		1948					
142	S 01° 20′, E 167° 23′	2 I	2	0	0	cu 1	LU
147	N 01° 06′, E 154° 42′ (Kapingamarangi atoll)	8 I	3	1	0	overcast	L S
151	N 02° 11′, E 145° 47′	13 I	4	1	1	frcu 2	SU
156	N 02° 44′, E 134° 58′	19 I	2	1	1	cu 1	SU
160	N 04° 43′, E 128° 07′	22 I	1	1	0	cu 2	B
165	N 00° 59′, E 127° 00′	29 I	1	1	1	cloudless	SU
179	S 07° 33′, E 114° 35′	7 II	1	0	0	cu, cunb 2	SU
180	S 07° 24′, E 113° 10′	15 II	3	1	0	cicu 2	SU
187	S 11° 03′, E 103° 49′	27 II	0	0	1	cu 2	BU
191	S 11° 25′, E 102° 13′	29 II	0	0	1	cu 2	L
192	S 11° 25′, E 102° 08′	29 II	0	0	1	cu 2	LU
193	S 11° 25′, E 101° 39′	29 II	0	0	1	cu 2	LU
201	S 08° 49′, E 88° 16′	6 III	1	1	1	ci, cu 3	B
206	S 02° 33′, E 88° 19′	9 III	2	1	3	cu 1	B
220	S 01° 22′, E 70° 28′	2 IV	5	2	0	cu 2	B
227	S 02° 13′, E 58° 43′	8 IV	2	0	0	cloudless	B
251	N 17° 29′, E 40° 22′	29 IV	0	0	0	cloudless	S
272	N 32° 12′, E 30° 13′	16 V	1	0	0	cloudless	B
277	N 33° 54, E 28° 17′	18 V	3	2	0	cloudless	LU
282	N 34° 24′, E 24° 00′	20 V	2	1	0	ci, cu 2	D
287	N 36° 13′, E 17° 28′	23 V	0	0	0	cloudless	D
294	N 40° 12, E 12° 21′	26 V	3	1	0	ci 1	L
338	S 00° 08′, W 18° 11′	13 VII	7	2	1	cloudless	B
340	N 00° 13′, W 18° 26′	15 VII	8	4	1	—	T
361	N 08° 15′, W 46° 30′	31 VII	7	2	1	cu 2	B
365	N 14° 32′, W 55° 05′	5 VIII	9	3	1	stcu 1	B
368	N 19° 04′, W 63° 02′	9 VIII	8	3	1	cu 2	B
371	N 24° 26′, W 63° 28′	21 VIII	0	0	1	—	T
372	N 24° 32′, W 63° 19′	21 VIII	3	1	1	frcu 2	BI
374	N 28° 33′, W 59° 49′	25 VIII	4	2	1	cu 1	BI
377	N 30° 38′, W 56° 05′	28 VIII	8	3	1	cu, ci 2	L
399	N 42° 35′, W 20° 57′	13 IX	6	3	1	cloudless	B

With some exceptions the measurements were carried out at noon local time and with a clear sun (a slight cirro-stratus haze is not avoided) affording the greatest possible constancy of the daylight. The solar altitude, which is an important factor when studying the radiant energy in the sea, is later given together with the results. In the weather column, in the sky when daylight was being me are reported according to the interna scale.

The positions of all stations referred this paper are marked on the chart in (triangles).

order to denote the purpose of the urement the following symbols are used e last column of Table 1.

Visible light (365—690 mμ), downward component

Short-wave radiation (295—490 mμ), downward component

Blue light (465 mμ), downward component

Horizontal component

Upward component

Angular distribution as measured with the aid of the directional photometer

Transparency as recorded by means of the transparency-meter

nus **LU** means that the downward as well s he upward component of visible light is le rmined, and **BH** means that the downward s well as the horizontal component of blue ig is measured.

Submarine Daylight

s radiation is a fundamental factor for the htoplankton production, the penetration and ribution of subsurface daylight is a subject f great importance. Recent advances in ntitative ecology of plankton (Riley, Stom- and Bumpus, 1949) have afforded new cts on the production in the ocean. It is eved that high temperature, through its ct on the sinking rate of plankton, may be th most important cause of the small concen- ions of plankton and the high transparency f ropical and subtropical waters. Here, the cal properties of the water itself clearly ear.

n this first part of the report about the cal studies of ocean water we shall deal n visible daylight comprising the spectral ge 350—700 mμ. Experiments were con- ted in the *euphotic* zone but some of them e extended down to 200 m.

Photometers

For measuring submarine daylight in the upper strata the well-known and simple photo-electric method with selenium rectifier cell has been employed. Three photometers were constructed, for a pressure up to 20 atmospheres, two small, which can be provided with an external colour filter, and a big one, within which an automatic change of colour filters is effected.

There is not much to say about the small photometer, which is a standard instrument closely described before (Pettersson and Poole, 1937). The Swedish type used is shown in Fig 1. The metal collar surrounding the window *W* holds the colour filter and, uppermost, the opal glass *O*. The filter rests on a thin flange in order to prevent leakage of light past the edge of the filter.

The case of the big photometer (Fig. 2) is cast in light metal (Hiduminium RR53C) manufactured by Weda-verken and anode-oxidized externally in order to reduce corrosion. The cable enters the case through a watertight gland *G* in the rounded lid *L*. This lid also belongs to the transparency-meter. Connected

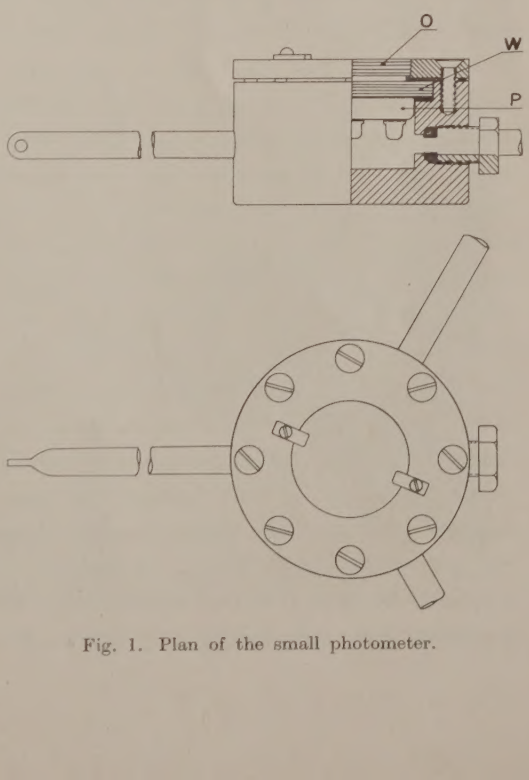


Fig. 1. Plan of the small photometer.

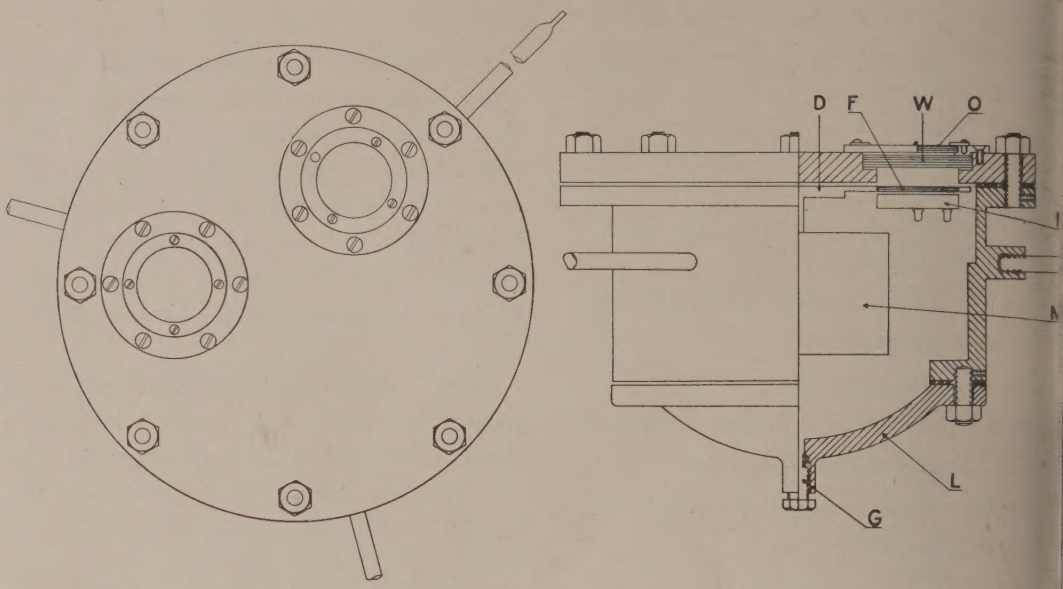


Fig. 2. Plan of the spectral photometer.

to the cable it is kept at the winch below the winch-cover.

The photo-cells are mounted below windows in the upper plane lid of 25 mm thickness. The windows are 60 mm in diameter, 12 mm thick and made up of Pyrex Brand Glass from Corning Glass Works. They are not symmetrically placed because of the arrangement of filters in the disc *D*, rotating between window *W* and cell *P*. The disc must be some millimetres below the lid in order to ensure its free rotation when the photometer is in deep water, where the rubber packings are compressed. Eleven colour filters and one free passage are contained in the filter disc. The filters are introduced in front of the cell in succession with the aid of a motor *M* operated from the laboratory. The entire assembly is similar to that devised by UTTERBACK and HIGGS (1938). It has proved most useful, in particular as the high efficiency of the motor requires only a small current to be lead through the cable together with the weak photo-currents. With the UTTERBACK and HIGGS photometer a simultaneous record of the upward and the downward light component is possible. We have found it easier to turn the photon face down to determine the upwardly scat light.

In order to effect the necessary reducti the illumination on the photo-cell a red screen is inserted above one window. screen, first used by HANS PETTERSSON, co of an »optical sieve» made by sandwichi sheet of tinfoil containing a number of eq sized and equally-spaced holes between an glass and a milk glass. When the photo is submerged the screened cell is used at until readings get small. Then it is ch for the other cell, the window of whi provided only with an opal glass, compa readings for all filters being taken a change. Thereafter the photometer is lo as far as the galvanometer at disposal is to react. Thus in one haul a complete urement is obtained.

The cable from the photometer vi winch to the laboratory is an eight-cond manufactured by Liljeholmens Kabelf Five conductors are used for the photo two for the motor and three for the photo The winch cable is united to the cable le

laboratory by means of water-tight ions with silver contacts mounted on e of the winch drum. These connexions ken when the winch is operated.

cable was connected in the laboratory EMENS and HALSKE light-spot galvano- (sensitivity $2.19 \cdot 10^{-8}$ amperes per nit, internal resistance 18 Ω) supplied extra shunt of 1: 3, 1: 10, 1: 30, 1: 100, 300. The instrument was placed on a

F. 3. The spectral photometer going down.

t on a static table, and its output was fected by shaking and by motion of the When measured in the surface stratum, output was often unsteady owing to real ons in the light received by the photo- the variations being caused by waves ell and by the raising and sinking of otometer because of the motion of the he latter effect could be greatly reduced ving and lowering the cable in the same

Fig. 4. The photometer winch.

phase as the ship motion so that the photometer kept its depth.

The photometers were suspended to their cables and moved out from the shadow of the ship with the aid of a 7 m crane pointing out from the stern of the vessel (Fig. 3). A loud-speaker at the winch connected to a telephone in the laboratory performed the necessary communication between the winch-manager and the observer at the galvanometer. The

Fig. 5. Daylight photometers mounted at the bowsprit.

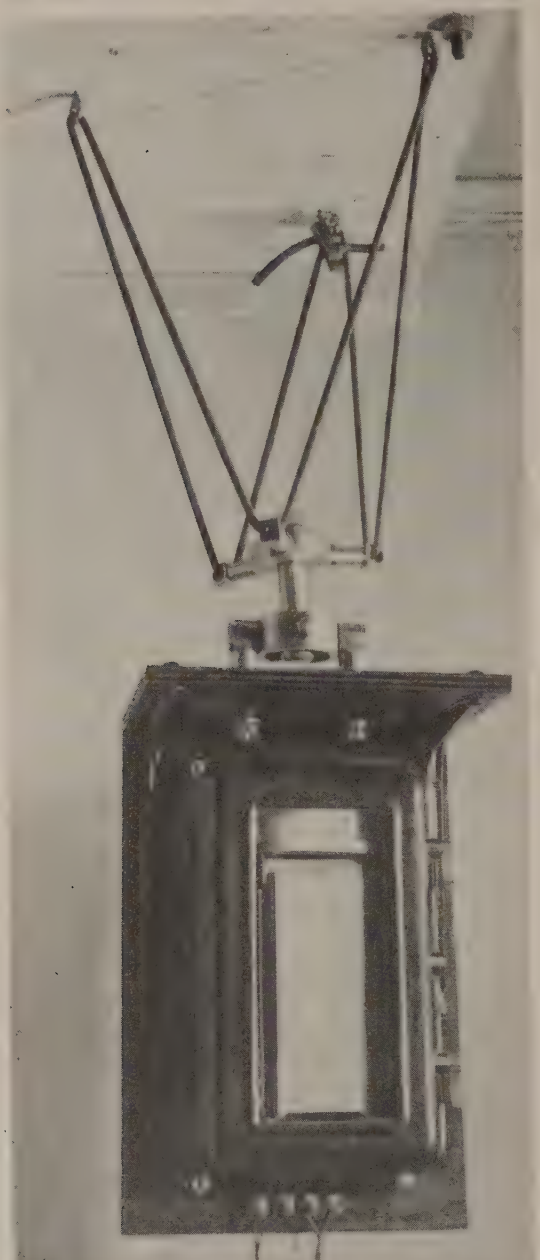


Fig. 6. Double-recorder suspended by rubber strings and used for recording daylight.

former also had to communicate with the officer on the bridge, who handled the ship carefully so as to keep the cable vertical. This often required much skill, as the photometer must never be in the shadow of the ship.

A deck photometer consisting of a p and a reducing screen, in cardanic n and freely exposed to the sun, recor small variations that might occur in th daylight during the measurement. deck photometer mounted at the (Fig. 5) was connected to a double suspended by rubber strings (Fig. 6), in spite of the motion of the ship unc records of the daylight were obtaine the whole journey.

Colour Filters

Colour filters should transmit highl a fairly narrow spectral block and be so as to cover the whole visible r differential system of working is partly This means that the difference between for two filters transmitting freely f far infra-red to a sharp limit in th spectrum measures the light in th between these two limits. With rega strong absorption of infra-red in w differential method may be useful in and in the yellow, whereas it is less in the short-wave spectrum, the mentioned being here small compare readings. Therefore, in the short-w filters cutting out at both sides h chosen. At great depths, however, v blue light predominates, the differenti is again to be employed for the gree blue. Filters or filter combinatio characteristic curves show a low tra maximum and long tails (*e.g.* VG have been avoided, as their sta tion data are hardly to be obta accuracy.

The colour filters were delivered b und GENOSSEN, JENA, and provi certificates for 1 mm thickness. It was to make allowance for the fact that were not exactly 2 mm thick. The tance of the filters was checked by BERGMANN spectrograph.

following colour filters were inserted filter disc:

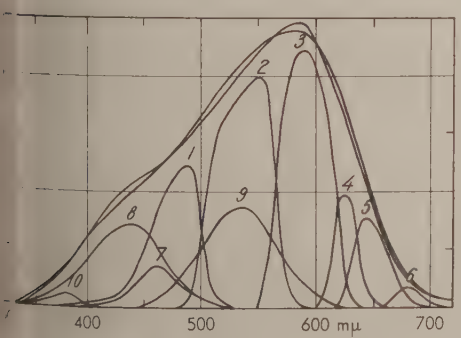
the differential filters
G14, OG1, RG1, RG2, RG5, and RG8.

ly the filters cutting out at both sides
3G12, BG12, VG9, and UG1+BG12.

n the spectral photometer was lowered
ing measurements, the two darkest
RG8 and UG1+BG12 were introduced
t of the photo-cells in order to avoid an
ssary intense irradiation of the cells.

Standardization

standardization of the spectral photo-
was performed according to a method
ted by JERLOV and OLSSON (1943).
ms at a comparison for definite spectral
. between the photocell and a thermopile
he sun as a light source and yields the
vity curve in absolute energy units for
al-energy spectrum within the visible
The disturbing infra-red is practically
ated from the solar radiation with the
filter BG19 from Schott u. Gen. As the
ng screen and even the windows of the
neter show selectivity to light, it is
ient to standardize the photometer as a
Thus a cylindrical screen one metre in
and admitting a narrow cone of light
l by four diaphragms was mounted above
indow and directed to the sun. As,
to small inequalities in thickness, filters



Sensitivity of the spectral photometer and with colour filters.

TABLE 2. Filter data.

Filter No.	Filter	Width mμ	Centre of gravity mμ	Sensitivity integral (mA per cal/cm² min × 1 mμ)
1	GG5 —GG14	50	475	60
2	GG14—OG2	60	535	115
3	OG2 —RG1	50	590	108
4	RG1 —RG2	25	625	25.7
5	RG2 —RG5	35	650	26.2
6	RG5 —RG8	20	680	4.5
7	GG5 +BG12	40	465	16.8
8	BG12	80	435	57
9	VG9	75	535	68
10	UG1 +BG12	30	375	3.5

of the same fusion sometimes differ slightly as to transmission, the same filters were used for the photometer as for the thermopile.

The conclusive standardization data concern the screened photo-cell and are given for the photometer in air and with the space between reducing screen and window filled up with water. Two sensitivity curves for the photometer without colour filter, the sensitivity being in mA per cal/cm²min, are shown in Fig. 7. One was obtained in May 1947 just before the start of the expedition, the other in July 1949 after the expedition. The small deviation in the trend of the curves is within the limit of experimental errors and cannot be attributed to any change in sensitivity during the long tropical cruise. Sensitivity curves for the photometer with the different filters are also presented in Fig. 7. Corresponding data about the actual spectral range, centre of gravity, and sensitivity integral are put together in Table 2.

Loss in Sensitivity

When a photometer is submerged and the external diffusing opal glass is immersed in the water, internal and external reflexion effects cause a loss in sensitivity of the photometer. POOLE (1936) has considered the matter and found that to correct for this the reading of an immersed standard photometer must be multiplied by 1.09. When measurements were

taken onboard the »Albatross» readings were often taken just beneath the surface as well as above it. From this, the loss of sensitivity may be derived, provided reflexion losses at the water surface with a high sun and a calm sea are estimated at 3 %. (See SVERDRUP, JOHNSON, and FLEMING, 1946). A number of such observations show that the standard photometer loses about 12 % in sensitivity. As this photometer is used only for relative measurements, the correction is not important. For the spectral photometer with its internal colour filters, on the other hand, a factor as high as 1.22 must be applied in order to get absolute energy values.

Spectral Energy Curves

The experimental results appear as galvanometer readings for the photometer with different colour filters and at different levels in the sea. The treatment of results is made on the basis of the response curves for an equal-energy spectrum given in Fig. 8 and aims ultimately at presenting spectral energy curves for the radiation incident on a horizontal surface at various depths.

Let E_λ be the sought radiant energy for the wave-length and p_λ the sensitivity of the response curve with assigned limits λ_1 and λ_2. The galvanometer reading R is then given by the formula:

$$R = \int_{\lambda_1}^{\lambda_2} E_\lambda \, p_\lambda \, d\lambda \qquad (1)$$

The centre of gravity λ_m for the response curve is defined by

$$\int_{\lambda_1}^{\lambda_m} p_\lambda \, d\lambda = \int_{\lambda_m}^{\lambda_2} p_\lambda \, d\lambda \qquad (2)$$

The energy E_{λ_m} at this centre may approximately be written

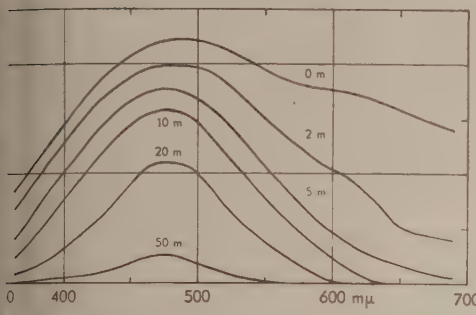
$$E_{\lambda_m} = \frac{R}{\int_{\lambda_1}^{\lambda_2} p_\lambda \, d\lambda} \qquad (3)$$

The sensitivity integrals $\int p_\lambda \, d\lambda$, i. surface of the response curves, are g the last column of Table 2.

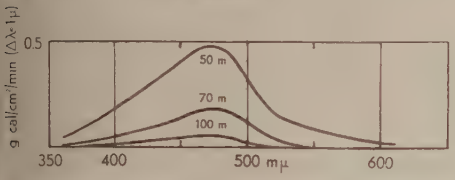
For sea water, which exerts a selectiv on light, the energy varies much wit length. The equation (3) for determi at certain wave-lengths may be useful p that response curves are narrow and sym al. This is not the case with some curves. Therefore, with increase of dep centres of gravity are shifted. In the where the blue light is most penetran are towards the blue, whereas the blu 1 and 7 are practically unshifted. In pa the wide green filters 2 and 9 are cons changed in deep water. Some scientis measuring submarine daylight have n due regard to this shift effect, which to serious errors. Recently JOSEPH (19 critically examined the use of some s filters and suggested that certain cor be applied in order to get the true ex

In our case these difficulties are Equation (1) is solved by approximati using Formula (3) a first spectral obtained, which is subsequently alte Equation (1) is satisfied. As shifts are from one ocean station to another this p is not very circumstantial.

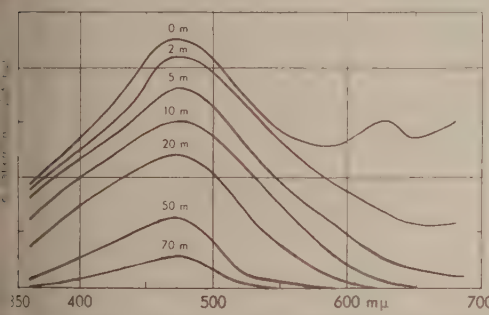
Complete measurements of subsurfa in different colours were made at eight The experiments were conducted unde sky and at a high solar altitude except 191, where the sun was only 31° ab horizon. Observations from this sta later used to discuss the influence of on the vertical extinction coefficien energy curves drawn with due re computed values for all filters are s Figs. 8—16, the energy in cal/cm²min by 1μ being given as the ordinate, wave-length as the abscissa. As measu usually could not be made just bene water surface because of the action and swell, the spectral curve for 0 m is c



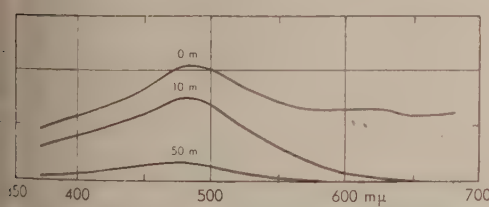
8. Spectral energy of the downward illumination. Station 29.



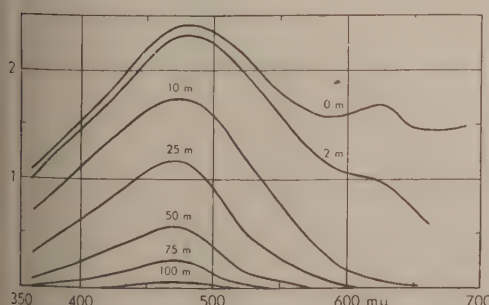
9. Spectral energy of the downward illumination. Station 108.



10. Spectral energy of the downward illumination. Station 142.



11. Spectral energy of the downward illumination. Station 191.



12. Spectral energy of the downward illumination. Station 192.

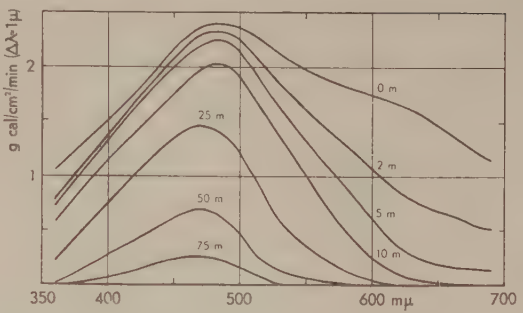


Fig. 13. Spectral energy of the downward illumination. Station 277.

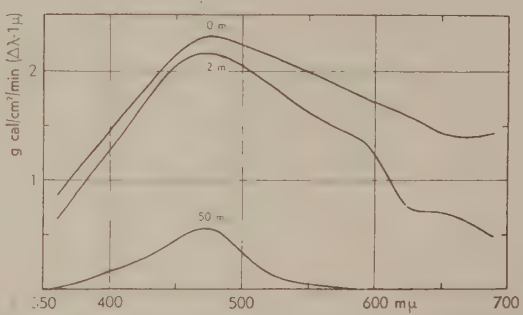


Fig. 14. Spectral energy of the downward illumination. Station 294.

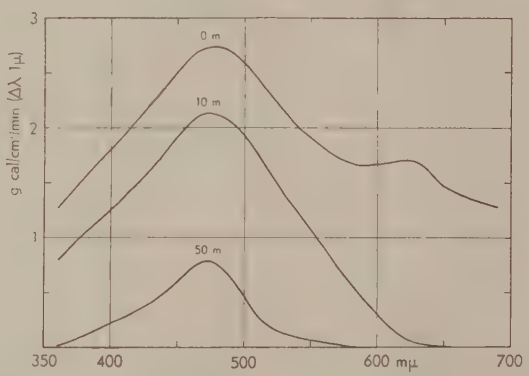


Fig. 15. Spectral energy of the downward illumination. Station 377, 0—50 m.

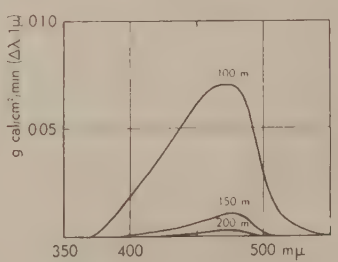


Fig. 16. Spectral energy of the downward illumination. Station 377, 100—200 m.

TABLE 3. Daylight energy between 400 and 700 mμ incident on a horizontal surface above the sea.

Station	cal/cm²min.
29	0.56
142	50
192	56
277	56
294	55
377	59

from observations with the photometer, in the air, above the surface, regard being paid to reflexion losses and to the aforementioned loss of sensitivity of the photometer when submerged.

Among the great number of readings there are some that do not bear a critical examination. For the long-wave end of the 2 m curve of Station 192 there is no accurate value. In the same case Filter 8 showed a much too low value, and so the curve is interpolated between Filter 7 and Filter 10. For 50 m at Station 377, made in rough weather, the ultra-violet is probably too low, but this value has not been disregarded in the later treatment. Filter 1 and Filter 7 in the blue serve to fix the maximum of the curves. Energy values for these two filters often differ to some degree for the surface stratum, but preference is given to the former for reasons already mentioned. With increasing depth the agreement improves and the position of the peak of the curves is ascertained.

The spectral distribution of the surface light shows a maximum at 480—500 mμ similar to earlier observations of daylight at high solar altitudes. Too much importance should not be attached to the absolute energy values. Systematic errors are introduced by the sensitivity integrals, which in some cases cannot be evaluated with a high accuracy. However, the amount of surface energy between 400 and 700 m for our stations (Table 3) accords well with similar measurements of daylight in the Indian Ocean made by Orth (1939).

When daylight penetrates the clear ocean water, the maximum intensity of illumination is slightly shifted toward short wave-lengt. The light distribution over the spectrum be 50 m exhibits certain inequalities for differ localities. In most cases the long waves more rapidly reduced with increase of de than are the short waves and consequentl salient asymmetry of the spectral curve developed, its maximum being at about mμ. This asymmetry is most marked for extremely clear water at Station 277 (Fig. in the East Mediterranean. On the other ha the 50 m curve is fairly symmetrical, ro 475 mμ, at Station 29 (Fig. 8) in the relati turbid water of the Carribean Sea. Ot stations are intermediate between these t extremes. At Station 377 measurements w extended as far down as 200 m. Fig. demonstrates how the energy curve narr with increase of depth. At 200 m the resid blue daylight is practically within the s range 430—500 mμ.

Extinction of Daylight in the Oceans

The series of spectral measurements exten to 50 m or more are presented from anot point of view in Figs. 17—21. The logarith

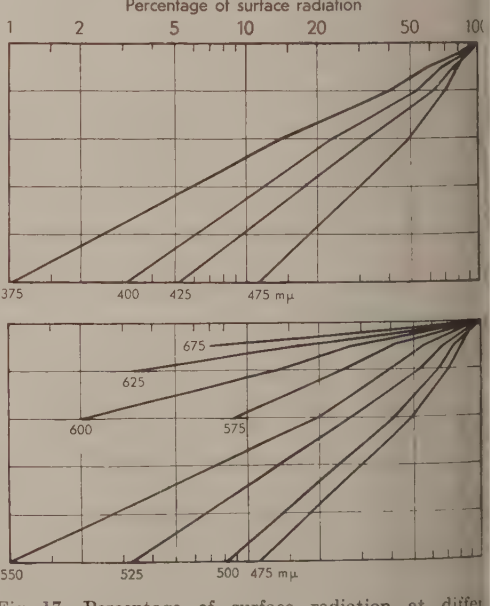
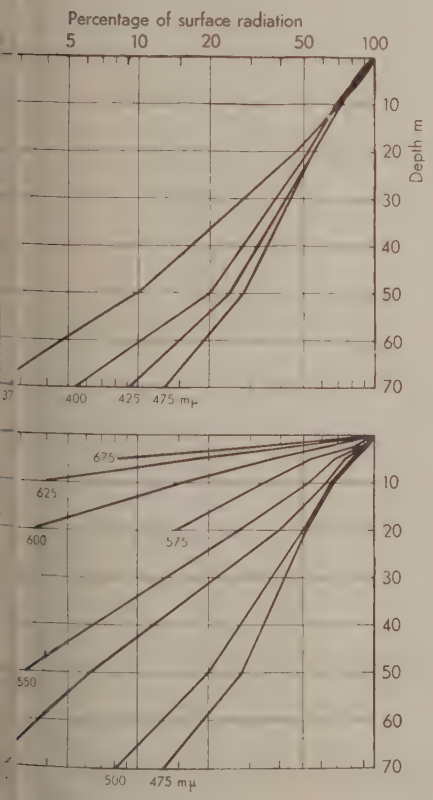


Fig. 17. Percentage of surface radiation at differ depths and for every 25 mμ. Station 29.

...low for every 25 mμ the percentage of ... radiation that reaches the various ... But the wave-lengths 450 mμ and ... are generally omitted, as they disturb ... dity of the graphs. Wave-lengths below ... and wave-lengths above 475 mμ form ...arate sets of curves. Wave-length 475 ... which the ocean water is most trans- ... is given in each set.

... the logarithmic curve the vertical ... on coefficient $\varkappa$ (PETTERSSON, 1936 a) ... mined. It is to some degree influenced ... sun's altitude at the time of the ... ement. This subject is thoroughly dis- ... later. The experiments were conducted ...udes varying between 65° and 90°. The ...ce is likely to affect the extinction less ... oes the inevitable experimental depth ... All extinction values dealt with here ... erefore, considered to be valid for a



Percentage of surface radiation at different ...pths and for every 25 mμ. Station 142.

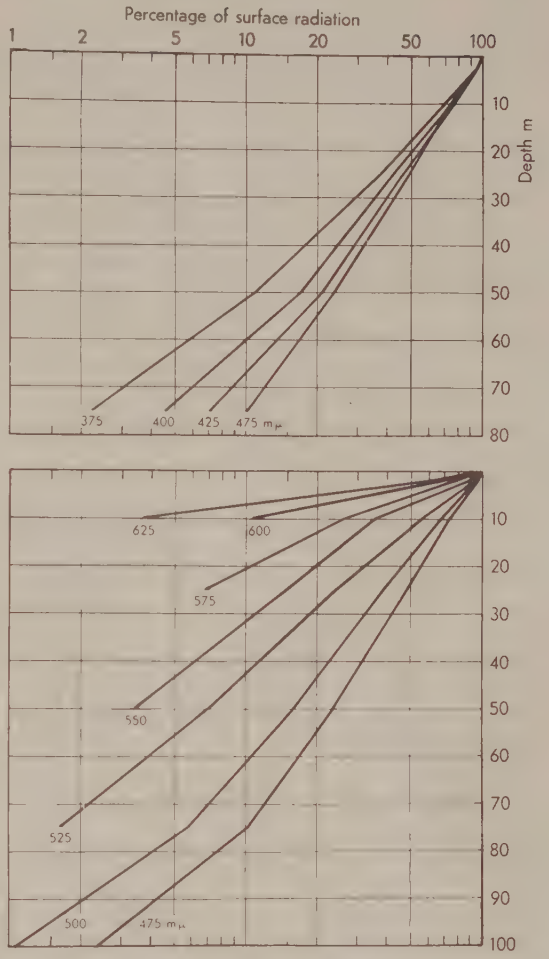


Fig. 19. Percentage of surface radiation at different depths and for every 25 mμ. Station 192.

zenith sun. In order to give a concrete idea of the reduction of light it is often convenient to use transmission per m depth T instead of extinction coefficient $\varkappa$.

$$T = e^{-\varkappa}$$

At first sight the curves show a typical feature. There is a bending of most logarithmic curves, the light being reduced less in the upper than in the deeper strata. This phenomenon occurs only in clear water and will be discussed later when the daylight penetration in the clearest natural water is treated.

It is also evident that the long-wave set

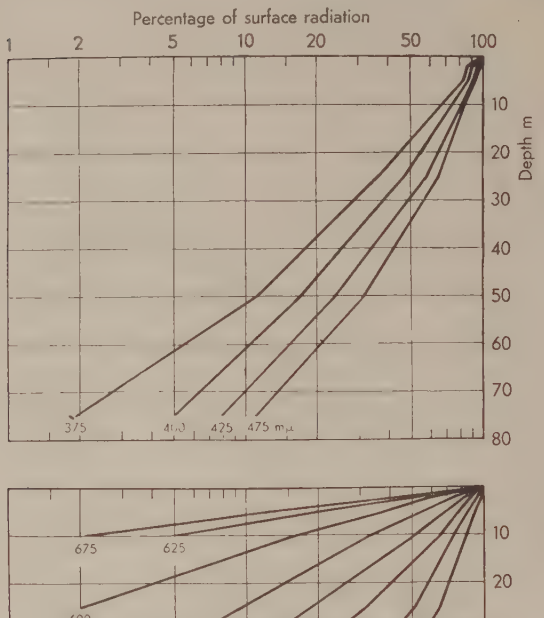


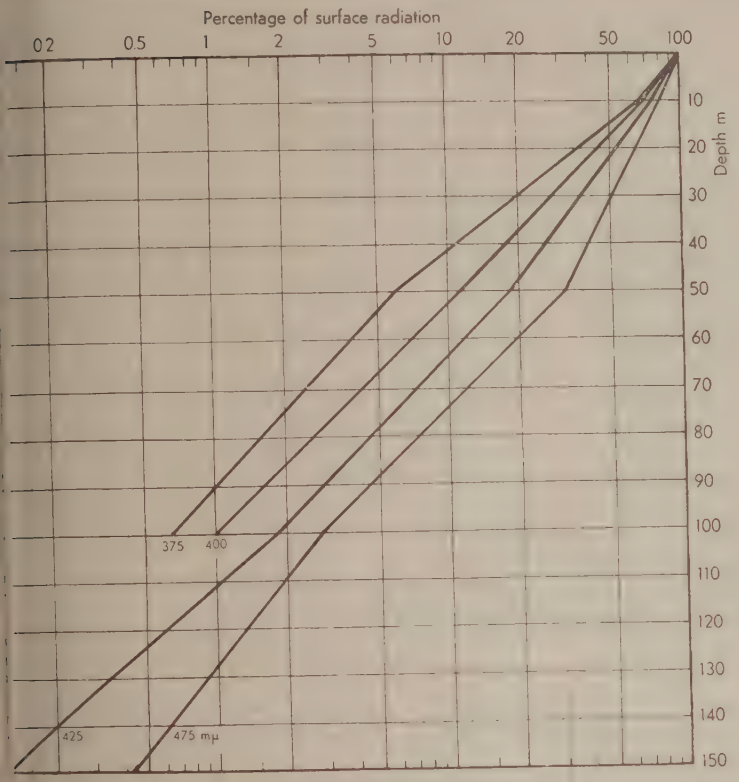
Fig. 20. Percentage of surface radiation at different depths and for every 25 m μ. Station 277.

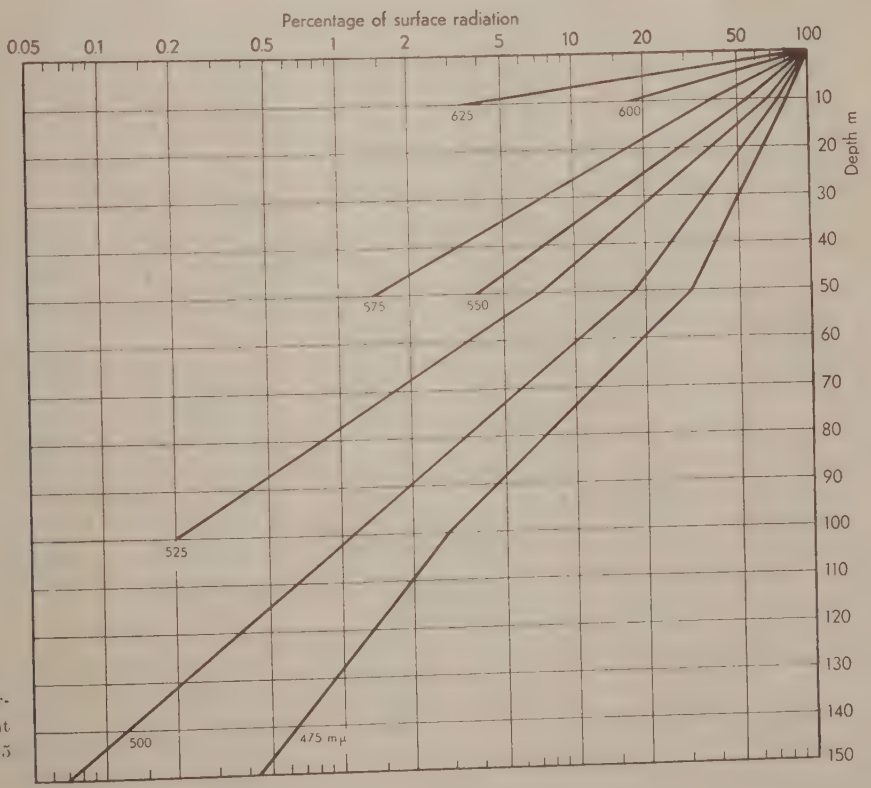
of curves 475—675 mμ covers a wider range of transmission than does the short-wave set 375—475 mμ, though the latter exhibits the greatest changes from one station to another. The appropriate comparison between different wave-lengths for the stations in question is carried out in Table 4. Here, mean t missions per m depth within the commo intervals are presented. The transmis the red recorded only in the surface not so accurately determined as to give evidence of any difference between the s In the extinction of red light the ab of the water itself predominates. At the stations begin to show individual value for Station 29 being definitely than other values. The deviations i mission increase towards short wave- Stations 142, 192 and 277 are very though the last station is slightly sup transparency. Stations 294 and 3 obviously lower in transparency and mu so is Station 29 in the relatively turbi of the Carribean Sea. None the l sweeping judgment can be expressed t tropical oceanic areas are fairly uni transparency.

Since the waters are best character their transmission to the ultra-viole should preferably be studied for this From reasons of intensity, however, th violet cannot be recorded by far so de as the blue. For investigating ocea parency by simple means I have pref use Filter 7 (GG5+BG12). As we ha there is no shift of the centre of gr this filter (465 mμ), and transmissio are easily derived. Observations of t component are apt to yield informatic dissolved matter in the water also, ch

TABLE 4. Values of mean transmission per m depth for various stations.

Station	Mean transmission per m depth									
	375 mμ 0—50 m	400 mμ 0—50 m	425 mμ 0—50 m	475 mμ 0—50 m	500 mμ 0—50 m	525 mμ 0—50 m	550 mμ 0—50 m	575 mμ 0—20 m	600 mμ 0—20 m	625 mμ 0—10 m
29	91.3 %	93.3 %	94.2 %	95.6 %	95.1 %	93.4 %	91.3 %	89 %	83 %	71 %
142	95.4	96.8	97.2	97.4	96.8	94.8	93.4	91	85	73
192	95.5	96.6	96.9	97.1	96.6	94.9	93.4	89	80	72
277	95.6	96.6	97.2	97.6	96.7	94.9	93.5	91	85	74
294	94.6	95.4	96.3	97.0	96.3	94.4	93.1			
377	94.4	95.6	96.5	97.5	96.6	94.9	93.7	92	84	71





. 21. Percentage of sur- radiation at different ths and for every 25 . Station 377.

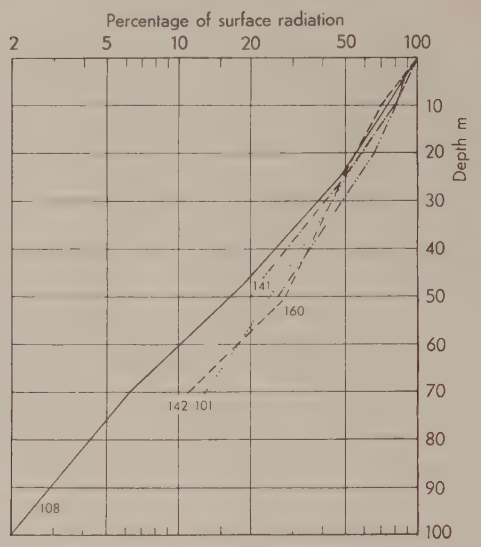


Fig. 22. Percentage of surface radiation (465 m μ) at different depths for stations in the Pacific Ocean.

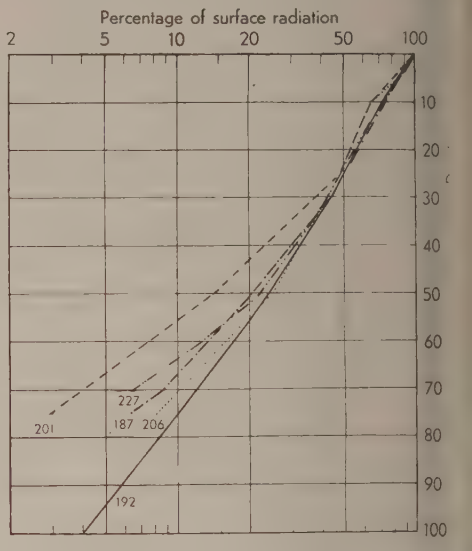


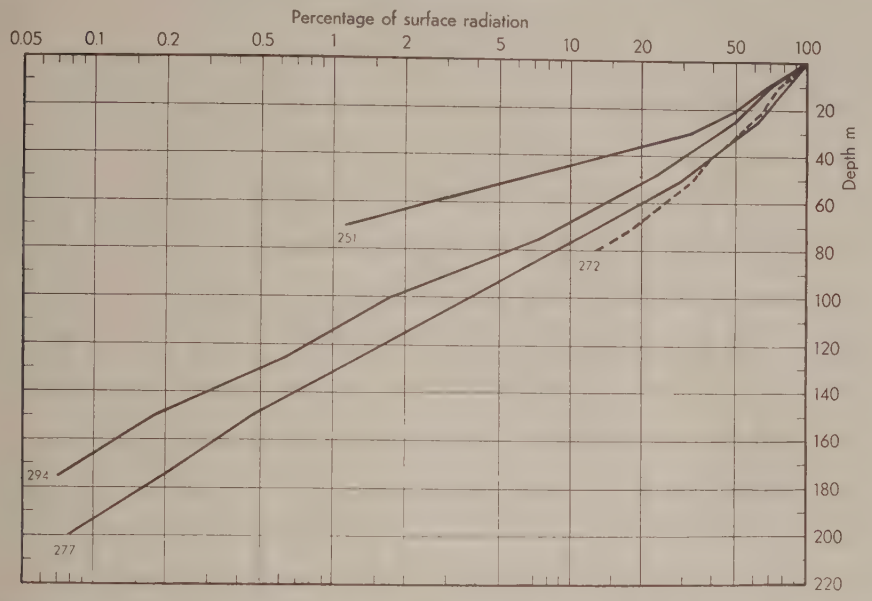
Fig. 23. Percentage of surface radiation (465 m μ ... different depths for stations in the Indian Ocea...

yellow substance. Thus, beyond the spectral measurements, experiments were conducted by means of the standard photometer provided with Filter 7. Results from all measurements with this blue filter are put together in Table 5, grouped for each ocean area. The corresponding graphs are submitted in Figs. 22—25.

We shall examine these results and give a survey of the transparency at the various localities. But, at first, some elucidatory notes on the results presented should be made. Irregularities often occur in the upper waters, chiefly because observations are uncertain. Contaminations from the ship have a noticeable effect on the extinction value. This effect, however, was avoided as much as possible, the ship being stopped just before measurements started. More serious are the depth errors. It could not always be ascertained that all parts of the cable kept vertical. In some cases, therefore, too high readings were found. For instance, the extinction between 75 and 100 m at Station 399 is no doubt somewhat low.

As regards the Pacific Ocean the first impression is that small variations in t... sparency occur horizontally. But the inv... gated waters do not include the impor... Galapagos region where observations, th... not accurate because of unfavourable weat... suggested a high extinction. Instead, ... transparency-meter was used at Station... and 53, and from the found values a ... estimation of the transmission to blue dayl... can be obtained at 91 % (extinction-coeffic... 0.095) and at 88 % (0.125) respectively. ... waters of the Galapagos with their abund... of particles and their origin for the most ... in the upwelling area west of South Am... may be considered as turbid for oceanic co... tions. This biologically productive are... extended through the South Equatorial Cur... and at the equator divergence far to the w... Still, Station 108 at longitude W 152°, ... just south of the Equator, diverges from ... cluster of curves in Fig. 22 and shows decisi... lower transparency.

Among other localities studied during ... cruise in the Pacific it is noticed that the w... in the atoll Kapingamarangi (Station 14... less transparent than the ocean outside.



24. Percentage of surface radiation (465 m μ) at different depths for stations in the Red Sea and the Mediterranean.

, in spite of the incessant inflow of ocean
er. The shallow water is here contaminated
particles which do not settle.

he Indonesia stations are reported in few
ds. Station 165 in the Molucca Sea
ains nearly oceanic clarity, whereas off the
th coast of Java (Station 180) the water,
taining particles in large quantities, is very
in transparency.

he Indian Ocean (Fig. 23) exhibits a similar
formity in transparency as was found at
st stations in the Pacific. The South
uatorial Current in the Indian Ocean does
carry turbid water as in the Pacific, rather
ter of high clarity (St. 192). A lower rate
transmission is discernible at Station 201,
efly because of abundance of particles, in
divergence at the Southern boundary of
Equatorial Countercurrent. The trends of
ier station curves in Fig. 24 deviate very
le from each other.

he curve for Station 251 in the central
rt of the Red Sea (Fig. 24) at a depth of
er 1,000 m shows a pronounced bending so
ly as at 20 and 30 m, below which it is
nearly a straight line. Furthermore, we can state that in the spring of 1948 the Red Sea water, characterized by a high salinity and a low content of particles, is much less transparent to blue light than is the average ocean water.

In this, the Red Sea contrasts with the Mediterranean. The east stations, especially Station 272, present a clarity which almost equals that of the Sargasso Sea. The intense blue colour of this Mediterranean area, which is indicative of a high transparency, is a well-known fact. At Station 294 in the Tyrrhenian Sea the rate of transmission is in all depth intervals somewhat lower than that at Station 277. This may be ascribed to the fact that the inflow of relatively turbid Atlantic water affects transparency conditions in the Tyrrhenian Sea.

Proceeding to the Atlantic the »Albatross» came across a great variety of waters with respect to optical character. The distribution of water masses in the eqatorial part of the Atlantic Ocean in summer is similar to that in the Pacific. A tongue of low temperature

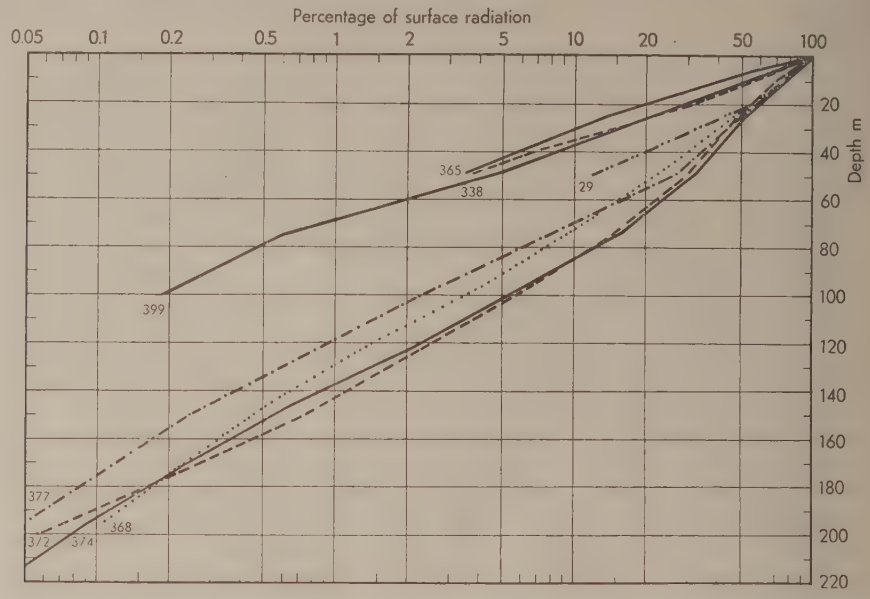


Fig. 25. Percentage of surface radiation (465 m μ) at different depths for stations in the Atlantic Ocean.

due to the divergence at the Equator extends towards west from the coast of Africa. In conformity with this, Station 338 (Fig. 25) at the Romanche Deep shows a fairly high turbidity.

Conditions in the West Atlantic are strongly influenced by the abundant outflow of dyed fresh water from the Amazon. Here the »Albatross» encountered narrow bands with greenish-blue water alternating with bodies of clear and blue water. Station 361 and 365 are in these blocks of turbid water. The latter station is carried out at a sun's altitude of only 32°, and so transmissions are here somewhat underestimated. In neither case was there an opportunity for a complete spectral investigation.

Station 368 was chosen at the south-eastern boundary of the Sargasso water. Its curve is a little lower in the upper strata than those of the typical Sargasso Stations 372 and 374, but all three curves converge further down. These two stations present the maximum clarity for natural waters, the water colour here being intense blue. The penetration through the first 100 m is as effective as ($\varkappa = 0.029$) but the next 100 m take a much more light, though letting throug good percentage ($\varkappa = 0.042$). Station 377 which a thorough spectral examination made, cannot be assigned to the Sargasso a as the transmissions are definitely lo Evidently this water approaches the condit at Station 399, which represents the tu water in the North Atlantic north-east of Azores.

Lastly, we will reconsider Station 29 in East Carribean Sea. It is well illustrated this curve joins the Sargasso curves surface to 20 m, after which it diverges becomes intermediate between these and Sta 365. These transparency conditions are sistent with hydrographical data. One br of the North Equatorial Current, whic characterized by clear water, flows into Carribean Sea where it is mixed with w of South Atlantic origin. This latter wat often highly dyed. At Station 29 an int mixing between the two water masses t place.

5. Average values of the vertical extinction coefficient $\varkappa$ for blue daylight (465 mμ) for the depth ranges indicated.

ly	Station	Sun's altitude	Depth range m	Vertical extinction coefficient $\varkappa$	Transmission per m depth %
n Sea	29	66°	2—10	0.031	96.9
			10—20	30	97.0
			20—50	52	94.9
Ocean	101	85°	2—10	21	97.9
			10—20	28	97.2
			20—70	29	97.1
	108	67°	2—25	30	97.0
			25—50	42	95.9
			50—75	46	95.5
			75—100	39	96.2
	141	62°	0—10	22	97.8
			10—20	26	97.4
			20—50	37	96.4
	142	61°	2—10	35	96.6
			10—20	24	97.6
			20—50	22	97.8
			50—70	48	95.3
	147	64°	0—5	60	94.2
	156	60°	0—10	31	96.9
	160	58°	0—10	22	97.8
			10—20	20	98.0
			20—50	31	96.9
sia Seas	165	65	0—10	38	96.3
	180	74°	0—10	104	90.1
Ocean	187	80	0—10	29	97.1
			10—20	26	97.4
			20—50	35	96.6
			50—75	45	95.6
	191	31	0—10	33	96.8
			10—50	29	97.1
	192	80	2—10	32	96.9
			10—25	24	97.6
			25—50	30	97.0
			50—75	34	96.7
			75—100	36	96.5
	201	86°	0—10	46	95.5
			10—25	18	98.2
			25—50	50	95.1
			50—75	63	93.9
	206	75°	0—10	44	95.7
			10—25	18	98.2
			25—50	26	97.4
			50—75	45	95.6
	220	81°	0—10	23	97.7
			10—20	32	96.9
			20—50	29	97.1
	227	65°	0—10	30	97.0
			10—20	30	97.0
			20—50	31	96.9
			50—70	62	94.0

Body	Station	Sun's altitude	Depth range m	Vertical extinction coefficient $\varkappa$	Transmission per m depth %
Red Sea	251	80°	0—10	0.038	96.3
			10—20	31	96.9
			20—50	70	93.2
			50—70	85	91.8
Mediterranean	272	74°	0—10	27	97.3
			10—20	17	98.3
			20—50	23	97.7
			50—80	31	96.9
	277	74°	2—10	20	98.0
			10—25	17	98.3
			25—50	30	97.0
			50—75	40	96.1
			75—100	44	95.7
			100—150	42	95.9
			150—200	36	96.5
	294	60°	2—10	35	96.6
			10—25	23	97.7
			25—50	34	96.7
			50—75	43	95.8
			75—100	57	94.4
			100—150	46	95.5
			150—175	37	96.4
Atlantic Ocean	338	63°	0—10	60	94.1
			10—20	57	94.4
			20—50	73	92.9
	361	65°	0—10	65	93.7
	365	32°	0—10	88	91.5
			10—25	74	92.8
			25—50	60	94.1
	368	80°	0—10	30	97.0
			10—25	32	96.8
			25—50	30	97.0
			50—75	35	96.6
			75—100	38	96.3
			100—150	41	96.0
			150—200	32	96.8
	372	65°	0—10	35	96.6
			10—25	24	97.6
			25—50	20	98.0
			50—75	29	97.1
			75—100	36	96.5
			100—150	41	96.0
			150—200	51	95.0
	374	66°	0—25	25	97.5
			25—50	21	97.9
			50—75	24	97.6
			75—100	41	96.0
			100—150	46	95.5
			150—220	38	96.3
	377	70°	0—10	29	97.1
			10—50	27	97.3
			50—100	49	95.2
			100—150	44	95.7
			150—200	40	96.1
	399	50°	0—25	63	93.9
			25—50	63	93.9
			50—75	80	92.3
			75—100	47	95.4

Comparison with Earlier Measurements

Reference has already been made to other observations in the oceans. UTTERBACK (1936) has used six colour filters covering the long-wave part of the spectrum beyond 460 mμ and has assigned the measured transmission values to distinct wave-lengths, disregarding the shift of centres. UTTERBACK's results indicate that in the oceanic waters off the coast of Washington the transparency can attain a value as high as 97.4 % per m depth in parity with the clearest oceanic water.

We have no reason to enter into a detailed discussion here about the light penetration in pacific coastal waters as studied by UTTERBACK (1936) and by YOUNG and GORDON (1939). We must also desist from comparing the present material, to the careful work done by ATKINS and POOLE (1937) in the Channel. Their results will later be discussed when sea waters are classified.

It remains to consider CLARKE's extensive investigations in the Mid Atlantic and in the West Atlantic (1933, 1936, 1941). Unfortunately his measurements of »green», and »violet» components in the sea are all impaired by errors due to the shift with increased depth shown by the centre of gravity of the recorded radiation. Only in his observations with the aid of a »blue» sensitized potassium cell is the necessary accuracy approached. Using this type of cell OSTER and CLARKE (1935) have found a marked bending of the logarithmic curve for a station in the Sargasso Sea. Apart from the fact that most of Clarke's transmission values, particularly in the upper water, are too low, his investigations yield valuable information about the distribution of transparency in the south-western section of the North Atlantic. Maximum of clarity was found south of Bermuda, consistent with our present data. There was a sharp drop in transparency off the coast of Guiana but not so far out as the »Albatross» in August, 1948, encountered turbid water. Our Station 29 and Clarke's Station 4: of the Small Antilles (CLARKE, 1938) a showing the fairly low transparency discussed. It is interesting to notice tha observed typical Sargasso transparency deep Cayman Sea west of Jamaica. suggests that this water is not mixed wit of South Atlantic origin.

Some words may be said about Sec observations. According to ATKINS and (1929), the extinction coefficient of light in the Channel can be expressed formula $\varkappa = 1.7/D$, where D is the m depth of visibility in metres as found Secchi disc. Comparing $\varkappa$ and D CLARK and GALL (1949) has found by expe appreciable deviations from this formula measurements by the Secchi disc ar to yield only inaccurate extinction coe in the surface water for a vaguely spectral range. It is no use to apply th sive results in our case. On the othe they give a rough picture of the dist of transparency in different water ar as far as a comparison is possible they stand in opposition to our results.

Submarine Daylight and Depth

Apart from its losses by reflexion water surface, the daylight is often sup be reduced considerably in the strat beneath the surface. POWELL and (1936) have found, especially in rough a lower transmission in the first metre they attribute to the effect of air bu the water. The »Albatross» measureme no evidence of such an effect. Natural small breakers produce some amoun bubbles in the surface stratum, but bubbles do not absorb but only scat light, their contribution to the extin apparently not important.

Reference has already been made fact that the vertical intensity of da measured by a horizontal photometer

f with increasing depth according to exponential law. The trend of the hmic curves exhibits a characteristic g, which mostly appears in the curves 00 mμ and is most marked at 50 or 70 m. aforementioned theory Le Grand (1939) own that, because of scattering effects, e of transmission is gradually diminished he surface down to moderate depths. ing to LAUSCHER (1947) the downward- tered light increases down to a certain which varies with the wavelength.

s easily understood that, as the photo- is being lowered it will receive scattered from an enlarging body of water. At however, the supply from the upper- layer is practically absorbed and does crease illumination at the depth of the neter. The effect discussed is likely to only for wavelengths that are highly ed and little absorbed. It is well devel- or the short-wave light, which indicates elective scattering plays an important For water where the absorption is strong s practically no bend in the logarithmic which is nearly a straight line (Station

he Red Sea (Station 251), which contains amount of particles but dissolved sub- this causing a fairly high absorption, tant rate of extinction of the blue as s of the ultra-violet is attained nearer rface than usual, or already at 20 m. w the characteristic bend, as far as rements have been extended (220 m), hmic curves seem to be almost straight The reduction of daylight in deep water ns more to an exponential law.

Submarine Daylight and Particles

us adopt the following notation.

total extinction coefficient (including absorption and scattering)

ertical extinction coefficient of daylight

A = absorption coefficient

S = scattering coefficient

Thus, by definition

$$c = A + S$$

If the persistent extinction coefficient by the water itself, c_w, is eliminated, the corresponding relation is obtained.

$$c - c_w = a + s,$$

where a = absorption coefficient by suspended particles and dissolved substance.

s = scattering coefficient by suspended particles.

As regards c_w it may be mentioned that its greater part is due to absorption. The scattering in pure water amounts at most to 20 % of c_w. By studying unfiltered and Berkefeld-filtered samples of sea water, CLARKE and JAMES (1939) have shown that s predominates over a in the extinction caused by contaminations in the water. The suspended matter exerts a pronounced selective action on light in coastal waters, but these authors could not prove a similar selectivity for ocean water. The Tyndall observations on board the »Albatross» reveal that the total scattering is higher in the blue than in the red. But, if the scattering produced by the water itself is deducted, the residual scattering s due to particles is only slightly selective. A comparatively non-selective action on light by particles in lake waters was also found by JAMES and BIRGE (1938).

The factors s and a are computed for the depth interval 0—25 m and correlated in Tables 6 and 7, the former representing clear ocean water, the latter more turbid ocean water. It is again demonstrated that the slightly selective scattering due to particles s is much higher than the absorption a for clear water, whereas in turbid water absorption even predominates. It is instructive also to insert in these tables values of the extinction of

TABLE 6. Comparison for clear ocean waters between total extinction coeff. c and extinction coeff. of dayli and between scattering coeff. by particles s and absorption coeff. by particles and dissolved substance a.

Wave-length	Double-distilled water Clarke a. James	Station 371				Station 108				Station 29		
mμ	c_w	c	$\varkappa$	s	a	c	$\varkappa$	s	a	c	$\varkappa$	s
655	0.303									0.36	0.33	0.06
540	0.068									0.13	0.06	0.06
440	0.022	0.07	0.02	0.04	0.01	0.11	0.03	0.06	0.03	0.11	0.04	0.07

TABLE 7. Comparison for turbid ocean water (see Table 6).

Wave-length	Double-distilled water Clarke a. James	Station 338				Station 46			Station 5	
mμ	c_w	c	$\varkappa$	s	a	c	s	a	c	s
655	0.303					0.40	0.07	0.03	0.42	0.08
540	0.068					0.22	0.08	0.07	0.28	0.09
440	0.022	0.14	0.06	0.08	0.04	0.20	0.08	0.10	0.27	0.10

daylight $\varkappa$. These are computed under the probable assumption that the mean path length is 120 cm.

The comparison between c and $\varkappa$ emphasizes the necessity of distinguishing sharply between these two factors, which as a rule differ significantly, at any rate for the short-wave spectrum. For clear water $\varkappa$ equals c_w, which shows that contaminations affect the penetration of daylight only to a small degree. The rôle of scattering in reducing daylight with increase of depth is illustrated by the simple relation

$$\varkappa = A + \gamma S,$$

where γ ($\leq 1/2$) is the fraction of the scattering that takes part in the extinction of daylight. If γ is estimated from values given in Tables 6 and 7, it comes out very small. This would suggest that scattering by particles is not uniform — in which case $\gamma = 1/2$ — but that it is performed through small angles, *i.e.* forward. This indicates that scattering is produced by refraction through comparatively large particles (see LE GRAND, 1939).

It may be gathered that, in the surface stratum of the clear ocean, scatter particles is fairly high and predominat absorption by particles and dissolved However, scattering does not very muc the penetration of daylight though thi as we have seen, increases with depth. fore, the extinction of daylight does n rule, give an indication of the con particles. The failure to find any cor between plankton content and extinc daylight is often stated. On the othe the presence of a stratum of particles i detected by means of the transparency which records the total extinction coe

Some new aspects on the scattering will appear when the colour of the discussed.

Submarine Daylight and Yellow Sub

The dissolved components of the oc firstly, the yellow substance, which selective action on daylight, secon accompanying substance exhibiting cence, which, however, seems to have influence on the optical properties water. The yellow substance is abu

l waters and chiefly responsible for their colour (KALLE, 1938). The heavy absorp- f the ultra-violet radiation in the surface of Skagerrak (p. 34) is caused by the substance. KALLE has shown its presence 1 the ocean at Jan Mayen by measure- in a Pulfrich photometer. The absorption for yellow substance according to KALLE is given in Fig. 26.

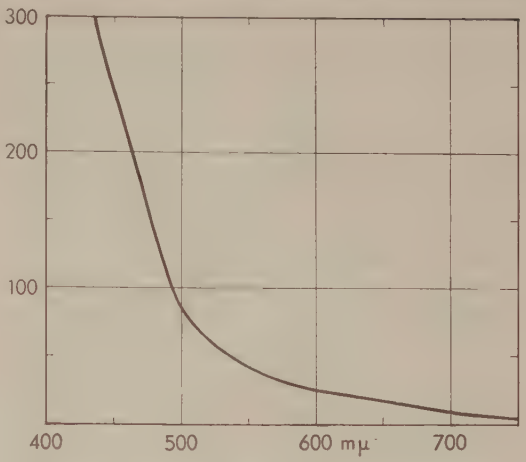
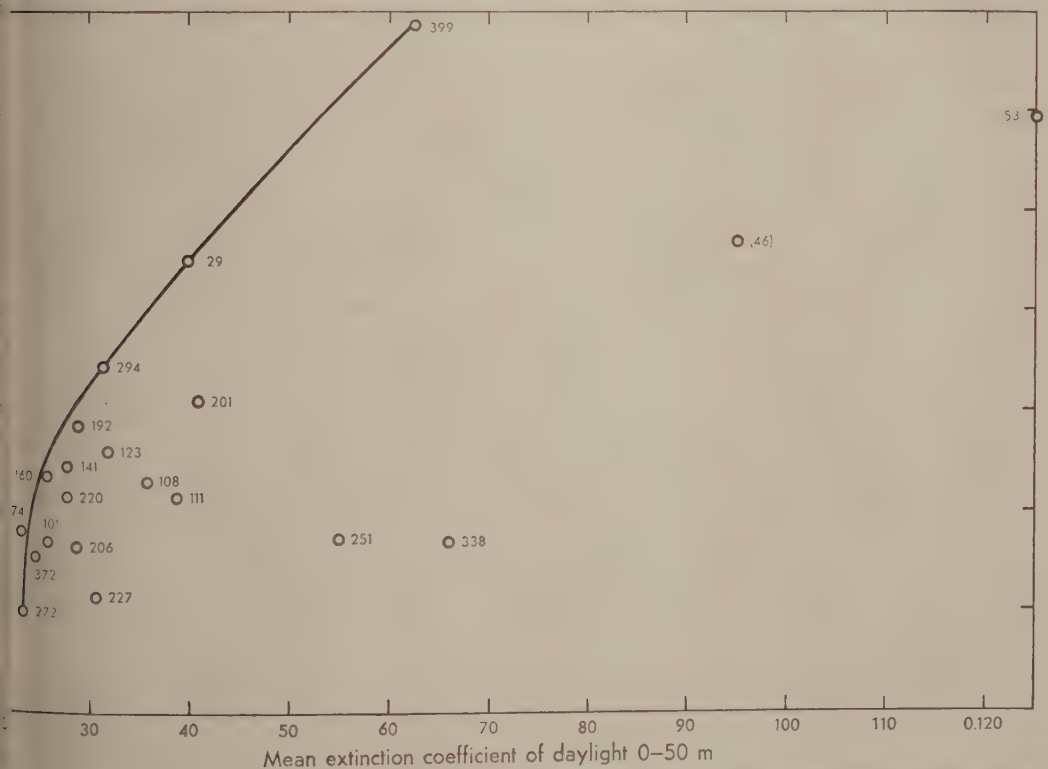


Fig. 26. Absorption curve for yellow substance (Kalle, 1937).

illustrating the effect of yellow substance ocean we will consider the mean extinc- oefficient in the uppermost 50 m for the ight of Filter 7 (465 mμ), which is highly ed by yellow substance. The extinction ient is compared with the total scatter- f blue light in the same depth column m as measured by means of the Tyndall atus (Fig. 27). In the graph, various ns are plotted for which both factors are nd. In some cases interpolation of the ring value has been made. Extinction coefficients for Stations 46, 53, 111, and 123 have been derived from measurements by the transparency-meter the results of which were repeatedly compared during the cruise with the extinction values for daylight. Thus, values



. Comparison for blue light and for different stations (0–50 m) between extinction of daylight and total scattering by particles.

for stations 111 and 123 are easily interpolated and may be considered as accurate. The positions in the graph of Stations 46 and 53 are somewhat uncertain, though not so much as to influence the discussion to come.

In the graph a curve is drawn to indicate the lowest extinction found for a given total scattering. Most stations are near or on this curve, which proceeds from the extremely clear water in the East Mediterranean (Station 272) and in the Sargasso Sea (Stations 372 and 374), via the West Mediterranean (Station 294) and the Carribean Sea (Station 29), to the relatively turbid water at Station 399 in the North Atlantic north-east of the Azores. The clarity of the South Sea (Station 101) and of the West Pacific (Stations 141 and 160) is again observable, whereas the Indian Ocean is at best slightly lower in transparency.

The bending of the limiting curve indicates that with increase of scattering the extinction of daylight is increased less in clear than in turbid water. This may be partly explained by the relatively low scattering produced in nutrient-rich water, where the particles are of larger average size than in less fertile areas. However, the selective absorption in turbid ocean water is, no doubt, largely due to yellow substance. For this argues also the observed water colour, which is chiefly determined by dissolved matter. These arguments also have a bearing on the following discussion.

Thus, the discussion suggests that yellow substance is practically absent in the clearest water whereas in water rich in particles a noticeable production normally occurs. But in the graph some stations fall out significantly from the limiting curve. In particular, this is the case for the Galapagos Stations 46 and 53. Let us consider values of scattering by particles s and of absorption by suspended and dissolved matter a computed as before and shown in Table 7. Stations 29 and 46 present much the same value of s, but at the latter locality a is considerably higher. ently the strong absorption in the Gal water, being pronouncedly selective, m largely attributed to an abnormally content of yellow substance. Station and 111, which belong to the outposts same water area, tend to a similar f Absorption also comes out prominen the Romanche Deep in the Atlantic (338). It is clear that in the upwelling west of South America and Africa, whic an abundance of particles, a rich pro of yellow substance takes place, and th turbid water is brought westward by cu Still, we must not preclude the possib a supply of yellow substance not onl the productive euphotic region but als deep layers of particles as detected Tyndall observations. According to W BERG (1937) disintegration of carboh takes place between 200 and 600 m ocean. It is relevant that in diverg somewhat lower transmission is foun particles as represented by scattering account for. As an instance Station adduced where observations were mad well developed divergence at the b between the Countercurrent and the Equatorial Current in the Indian Ocea as mentioned, the lower transmission this case partly be due to the presenc particles in the nutrient-rich water.

The water in the Red Sea represe Station 251 possesses a peculiar prop spite of a low content of particles — the ing is studied for every 10 m — it pr relatively low transmission to blue lig selective extinction of the short wav is in the Red Sea similar to what was other waters of the same turbidity. Ap the water contains a dissolved yellow component. As the supply of yellow s is not expected to be above the nor probable that the component is decomposition products of certain al

mium erythraeum, often giving a red or
n discoloration to the Red Sea.
e problem of yellow substance that
ntly concerns the penetration of the
violet is also dealt with in the report on
irements of the short-wave solar radia-
(p. 34). It appears that tropical rivers
Station 180) carry much less yellow
nce than for instance Scandinavian
. Thus, the Nile supplies the East
erranean with only a small amount of
substance, for its great outflow does
the long run affect the high transparency
s water.

marine Daylight and Physico-Chemical Environment.

have seen that *currents* govern the
bution of light-reducing factors in the
to a considerable extent. In particular,
l water from the upwelling areas west of
a and South-America is transported
ward by currents. Vertical movement as
vergences is also likely to affect the
parency.
the ocean a high *salinity* is often associated
a low content of particles. An anomalous
temperature indicates upwelling water
is rich in particles. Between the factors
rned, however, there is no correlation of
al application. Ultimately the phyto-
ton density in the illuminated euphotic
depends on the presence of fertilizing
nutrients. The relation between particles
nutrients is treated in another report. It
be concluded that the rate of extinction
ylight, which is not only a function of
les but also of dissolved substances, is
kely to stand in a clear relation to any of
liscussed factors.

tinction in the Clearest Oceanic Water.

special interest is attached to the clearest
encountered in the oceans. It will be
ed that one purpose of these measurements

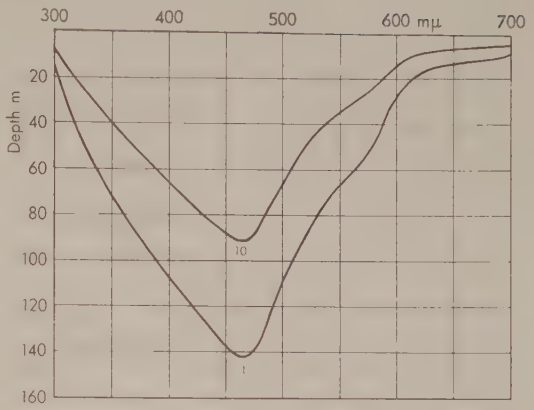


Fig. 28. Depths at which the percentage of surface radiation is 10 % and 1 % respectively for different wave-lengths in clearest ocean water.

was to determine the maximum transparency to daylight in natural waters. The question arises about the illustration of results ascertained by observations in the Sargasso Sea and the East Mediterranean beyond the logarithmic curves already given, which do not present a concrete picture of the reduction of daylight in different colours. It is preferable to show for the whole spectrum the depths z_{10} and z_1 at which the percentage of light is 10 % and 1 % of the surface value respectively (Fig. 28). Values of the ultra-violet extinction at 310 mμ as derived from special measurements are also used in this graph. Table 8 supplies transmission data for double-distilled water according to CLARKE and JAMES (1939), which are practically identical with their values for Berkefeld-filtered sea water. Mean transmission values for clearest ocean water in the depth intervals 0—10 m, 0—z_{10}, 0—z_1, and z_{10}—z_1 are also shown. For wave-lengths $\geq$ 575 mμ and for wave-length 310 mμ depth ranges are small and the same transmission value comes out for all of them.

A comparison between values in the first two columns of Table 8 reveals that the light-transmitting power of the clearest ocean water 0—10 m is close to that of double-distilled water. With regard to the accuracy attainable a difference is corroborated only for wave-lengths

TABLE 8. Comparison between transmission (percent) per m for double-distilled water (CLARKE and JAMES, 1939), and mean transmission per m depth for clearest ocean water and for the depth ranges indicated. The depths z_{10} and z_1 at which the percentage of light is 10 % and 1 % of the surface value respectively.

Wave-length mμ	Double-distilled water CLARKE a. JAMES	Clearest ocean water			
		0—10 m	0—z_{10} m	0—z_1 m	z_{10}—z_1 m
310		86	86	86	86
375	95.6	96.3	95.7	95.0	94.0
400	95.8	97.2	96.4	95.8	94.7
425	96.8	97.8	96.9	96.3	95.3
450	98.1	98.1	97.2	96.7	95.8
475	98.2	98.2	97.3	96.8	95.9
500	96.5	97.2	96.4	95.9	95.2
525	96.0	96.1	95.1	94.7	94.2
550	93.3	94.2	93.4	93.4	93.4
575	91.3	92	92	92	92
600	83.3	85	85	85	85
625	79.6	74	74	74	74
650	75.0	70	70	70	70
675	69.3	65	65	65	65
700	60.7	58	58	58	58

375—425 mμ, the ocean values being here slightly higher. The transmission to daylight in clearest water is given per m depth. If allowance is made for the mean path length of rays, transmissions should have been somewhat increased. On the other hand, the extinction of daylight in the surface stratum is, as we have seen, mainly due to absorption by the water itself. This explains why it could be less than extinction by double-distilled water, which is made up of absorption and scattering (and the scattering of short wave-lengths by the water itself is considerable).

Towards deep layers the transmission values decrease according to the characteristic trend of the logaritmic curves. In the interval z_{10}—z_1 they have attained constant values, which are maintained down to great depths.

Ultra-violet Radiation

The ultra-violet region of the radiation from sun and sky is made up of UVA (315—400 mμ) and UVB (280—315 mμ). The latter portion, though carrying little energy, is very signi in effecting the production of vitamin D having antirachitic effects, and of eryt During the Swedish Deep-Sea Expediti UVB radiation was measured by a technique, which is described below, wh UVA at 375 mμ could be recorded in the way as visible light. Besides the ultra- the blue daylight was studied simultane all observations being confined to the uppe 10 or 15 m. In this chapter the short region of the spectrum is treated as a though the blue and the near ultra-vi already discussed to some extent.

UVB Filter

For measuring the solar UVB ther obvious advantages in employing a s method *in situ*. A suitable method has been thoroughly discussed and used success at Bornö Station. The filteri effected through two liquid filters, suphate solution absorbing visible light e green, and picric acid solution elimi UVA, together with a UG5 glass from S and Gen., which reduces visible light an infra-red but still possesses high transpa to the UVB. These filters are combined photo-cell. Its surface is covered with

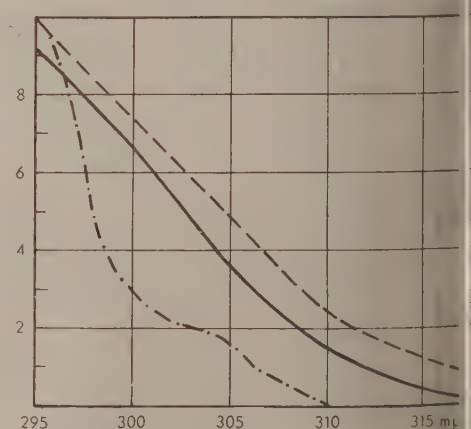


Fig. 29. The UVB filter (——). Absorption sp for non-irradiated ergosterin (— · —). Absorption rum for ergosterin as a product of short irradiation

tive quarz glass instead of the usual coat, which absorbs ultra-violet.

is, the UVB filter is made up of 18 mm ited nickel sulphate solution, 14 mm acid solution (45 mg per litre), and 6 G5. The filter curve is shown in Fig. 29. ldition, the absorption spectra for ergo- e according to ELLINGER (1935) are , for non-irradiated ergosterine as well r ergosterine as a product of short ation. The special range in sunlight nsible for vitamin D production in the is supposed to lie between these two terine curves.

e absorption of picric acid solution in oncentration and thickness used has been mined by means of a UV-spectrograph. found that its transmission extends to t 320 mμ, or somewhat farther than ved by Seitz (1933) (about 310 mμ). e UVB filter curve (Fig. 29) shows a ed transmission at 315 mμ and then rises ily towards shorter wave-lengths. The r limit of the filter does not exactly ide with the assigned UVB limit but lies what higher. Towards short wave-lengths absorption of sunlight by atmospheric

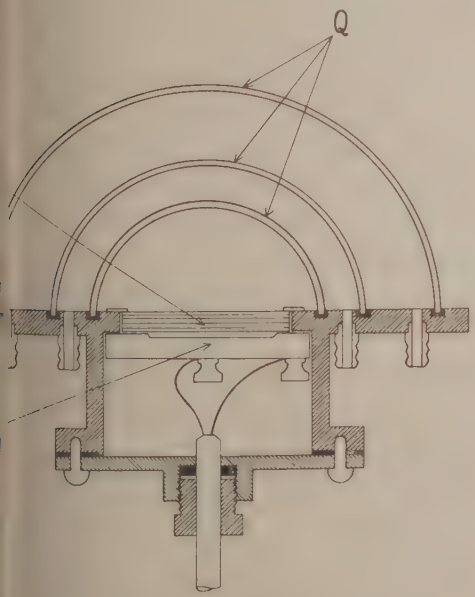


Fig. 30. Plan of the UVB photometer.

Fig. 31. Measuring the antirachitic ultra-violet daylight.

ozone gradually increases, so that there is practically no energy below 295 mμ in the daylight spectrum. The centre of gravity of the measured radiation is dependent on the composition of the daylight, which varies with solar altitude, cloudness and turbidity, and on the opacity of the water. It can be estimated at 310 mμ, with an insignificant error.

Photometer

It is not advisable, as in photometers for visible light, to use an opal diffusing glass. In opal quartz glass the UVB is strongly reduced because of high scattering. Instead, liquid filters were enclosed within hemispherical shells round the photo-cell so that oblique rays in the water could also reach the photo-cell. By this arrangement the photometer also attained a high sensitivity.

The photometer is shown in Figs. 30 and 31. Its three concentric hemispherical shells made

Fig. 32. Reading the ISING galvanometer.

from fused quartz 2 mm thick were manufactured by Thermal Syndicate, Wallsend. The outermost interspace, 18 mm thick, contains nickel sulphate solution, the inner one, 14 mm, picric acid solution. Filling is effected through the nozzles, thereby avoiding air bubbles in the liquids. The nickel sulphate solution can be preserved, whereas fresh picric acid solution must be prepared for each measurement. In order to compensate for the expansion of the liquids the nozzles are closed by thin india-rubber tubes some centimetres in length. The quartz shells are cemented to a metal ground plate with pizein. In order to prevent direct contact between the liquids and the metal the inside metal between the shells is covered with a thin layer of ceresine. The photometer is provided with a lid, which protects the shells and is removed only when the instrument is used for measuring.

The UG5 glass is flush with the ground and the photo-cell is in contact with its side. Even oblique rays falling on the filter are mostly refracted to the photo-c that the sensitivity of the photometer not vary much with angle of incidenc ATKINS and POOLE's (1936) integrating photometer). This means that the p meter does not measure the vertical com of daylight only but rather overvalu oblique rays.

The photometer is connected through a to an ISING galvanometer (sensitivity 4 · amperes per scale-unit). This galvano with a cardanic mounting and an oil sup is highly qualified for work at sea (Fig

Table 9 shows some experiments devis check any sensitivity of the photomet radiation outside the UVB. The photo reacted to a limited beam of direct su into which the GG18 (2 mm) and RG8 (2 filters were introduced in succession. former has a sharp cut-off at 370 mμ latter at 685 mμ. It is obvious tha disturbing effect is attributable to inf rays, which according to the filter pro are at 900 mμ. It amounts to less tha of the deflection, but as the diffuse sk predominating in the UVB carries very energy in the infra-red, the error due to red leakage is negligible. The strong abso in water of 900 mμ infra-red must al taken into account. Another test was mad the aid of a mercury lamp and a BG12 (2 mm), which at a tenth of maximum

TABLE 9. Sensitivity of the photometer to ra outside the UVB.

Mercury lamp		Sun	
Filter	Scale-units	Filter	Scale-
—	450	—	4
GG 5	0.3	RG 8	
BG12	0.2	GG18	

TABLE 10. Transmission values (percent) per m depth for short-wave daylight.

...on	Solar altitude	Depth m	UVB filter (310 mμ)		UG1+BG12 (375 mμ)	GG5+BG12 (465 mμ)
			Transmission per m depth	Extinction-coefficient	Transmission per m depth	Transmission per m depth
7	overcast	0—1	80 %	0.22		
		1—2	77	26		
		2—3	78	24	90 %	94 %
		3—4	76	27		
		4—5	71	34		
1	60°	0—5	90	10	93	
		5—10	86	14	95	97
		10—15	82	20		
6	61°	0—5	86	14	97	97
		5—10	85	16	93	96
5	66°	0—5	84	17	94	97
		5—10	81	21	93	95
9	75°	0—5	70	36	90	94
		5—10	70	36	90	
0	78°	0—2	44	82	75	90
		2—5	50	70	77	85
		5—10	70	36	87	91
7	62°	0—2	83	19		
		2—4	90	10	97	98
		4—6	87	14		
		6—8	84	17	96	98
		8—10	88	12		

... range from 325 to 490 mμ. It proved ... UVA was practically eliminated.

...e photometer attached to its cable was ...ed at the outer end of the 7 m aft crane ... »Albatross». Measurements were made ...ar and calm weather down to at most ... Some of them were carried out in the ...w waters of Indonesia, where the dis...ng effect of the ocean swell is small.

...e near ultra-violet was studied by means ...n ordinary photo-electric photometer ...ied with a 2 mm UG1 + 2 mm BG12 ... In order to connect the ultra-violet to ...isible region the extinction of blue light ...lso observed in the same way by using ...mm GG5 + 2 mm BG12 + 3 mm NG5

Transmission Values of Short-wave Daylight

As mentioned, the measurements were concentrated to the Western Pacific and to the Indonesia Seas except Station 277, which represents the extremely clear water in the East Mediterranian (Table 10). Station 151 and 156 are in off-shore waters but Station 165 is within the Molucca Archipelago. Station 147 inside Kapingamarangi atoll is affected by the proximity of land, and so the transparency is somewhat lower than in off-shore waters. The decrease of transmission towards the bottom indicates that whirling up of sediments in the atoll is highly responsible for the contamination. When coasting along Java in the Madura Strait and approaching Soerabaia we observed a gradually decreasing trans-

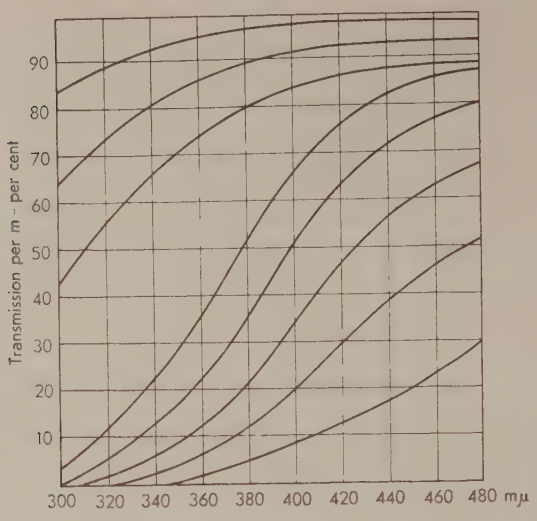


Fig. 33. Transmission curves of the short-wave radiation from sun and sky. The upper set of curves represents ocean water (solar altitude 90°), the lower set coastal water (solar altitude 45°).

parency, this being due to the mixing up of turbid water from rivers. Station 179 was made in a water of slightly greenish-blue tint. At Station 180, made when leaving Soerabaia *en route* for Bali, the water colour was still more greenish, but the turbid water was very shallow here, only about 5 m deep. The highest transmission through the 10 m column was found at the Mediterranean Station 277, where the clarity of the water is equal to that in the Sargasso Sea.

The experiments were conducted at a high solar altitude and the results may very well be valid for zenith sun, since the corrections to be applied for change of mean path length are negligible. If allowance is made for the mean path length, which with high sun is probably about 120 cm, the transmissions presented in Table 10 will be somewhat higher. But it is best to desist from introducing any minor corrections for mean path length and to consider the transmission values obtained per m depth as representative of zenith sun and of the surface layer. The experimental errors could be set aside by applying a procedure elaborated by JERLOV and KULLENBERG (1946). The transmissions derived for the and ultra-violet portion of the spectrum designated normal transmission values shown later in Table 31. Centres of gr have been estimated for GG5+BG12 at mμ, for UG1+BG12 at 375 mμ, and for filter, as mentioned, at 310 mμ. These n values are demonstrated by the upper s curves in Fig. 33. In the blue the varia keep within a narrow range of high t missions, whereas in the UVB they ex over the interval 86—50 %. On the w these curves may be considered as ch teristic of the tropical and subtropical re of the oceans. There are, however, no obs tions to decide whether the Galapagos with its abnormally high content of y substance fits into this scheme.

Quite another appearence is presente the lower set of curves in Fig. 33 earlier de from measurements taken under a solar alt of 45° at Bornö Station in the Gullmarf The rapid falling off of transmissions tow shorter wave-lengths is here largely du yellow substance. The surface water alon Swedish west coast is usually mixed up Baltic Sea water containing much y substance, mostly originating from r whereas in deeper layers inflowing North water has a lower content of this subst In the fjord, which is also supplied with water, there is a continual interchange bet different surface waters, and this account the great variations in transmission to ultra-violet. Even in the clearest water occ at Bornö at most 10 % of UVB are transm per m depth. At Madura the ultra-vio not by far so rapidly reduced. Here par — mainly terrigenous material — are responsible for the selective action on violet, the content of yellow substance evidently fairly small.

Thus, between the ocean and the seas Sweden a fundamental difference in o qualities has been demonstrated, this

; due to different contents of the dissolved
· component and also of the less important
ınce exhibiting fluorescence. The differ-
appears in the colour of the sea, which
latter areas is shifted from natural blue
enish colours.

cerning the ultra-violet at 375 mμ the
s are in conformity with earlier observa-
CLARKE and JAMES' (1939) laboratory
ırements showed that »pure» sea water
its a transparency of about 95 % at 365
From the uppermost curve in Fig. 33
ıme value is obtained. The comparison
; permissible in a strict sense for reasons
already.

the other hand, the low rate of absorption
VB in ocean water revealed by our
vations stands in strong opposition to
r laboratory results as reported by
URT (1928) and SAWYER (1931), even if
egard is paid to the discrepancy that
exist between laboratory experiments and
observations of daylight. The salient
of this investigation is that the penetra-
of the ultra-violet at 310 mμ from sun
sky is as effective as 86 % per m depth
clearest ocean water. This casts a new
on the biological problems connected
the ultra-violet clima in the ocean. The
-chemical processes in which UVB plays
e can be enacted within a considerable
ın of water. The active region in the
st ocean water may extend down to 20 m.
he scant presence of particles or objects
he irradiation in the ocean is naturally
sumption for the high clarity.

far, very few data have been collected
the influence of the ultra-violet on the
s in the sea and as to the relation of
adiation to animal ecology. It has been
ved that in several cases the ultra-violet
has a small assimilatory property (JERLOV
EVRING, 1946). No injurious effect of the
-wave radiation on plants has been reported.
other problem concerns the important
rôle of the UVB in the production of vitamin D. It seems as if this production is poor on account of irradiation. Some higher algae growing just below the surface or floating in the sea possess some anti-rachitic properties. For instance, DARBY and CLARKE (1937) found that the *Sargassum* weed exposed to intense active radiation in the extremely clear Sargasso water contains a small amount of vitamin D. According to JERLOV and LEVRING (1947), *Fucus vesiculosus* shows indications of anti-rachitic potency. Plankton oil derived from phytoplankton in coastal areas, though containing provitamin, does not possess a noticeable anti-rachitic action. As to zooplankton a slight amount of vitamin D has been observed as a result of irradiation with UVB.

Angular Distribution of Submarine Daylight

During the Swedish Deep-sea Expedition there were plenty of opportunities to study the distribution of daylight in clear and in deep water. The problem was attacked partly with the aid of the ordinary small photometer turned upwards, downwards, and in a horizontal direction. In some cases the spectral photometer was arranged so as to measure the upward intensity over the whole spectrum. These instruments were lowered so deep as to react to the light with the galvanometer at our disposal. For a close study of the angular distribution a photometer was devised that allowed of the intensity in any direction in the water being determined. By means of this photometer a directional character of the submarine daylight could still be ascertained at 100 m depth, but for the most part it was used only in the surface layer in the Mediterranean.

Directional Photometer

This apparatus is similar to that used by JERLOV and LILJEQUIST (1938). A brief description is given here. The photo-cell receives a

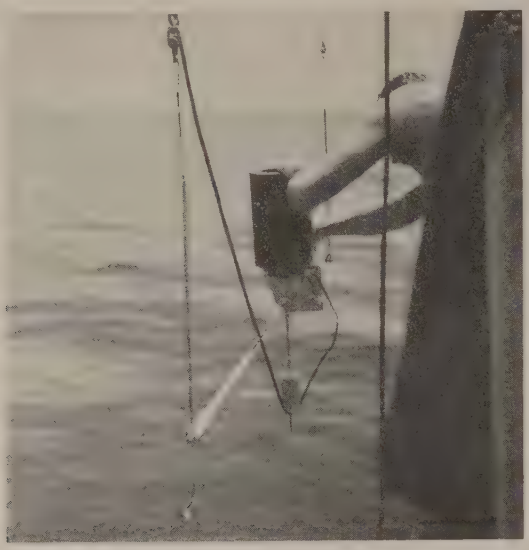


Fig. 34. The directional photometer is adjusted.

narrow cone of light (15° aperture) limited by three diaphragms of a cylindrical screen. The diaphragm close to the cell is provided with a circle of holes screened from light round the photometer case, this in order to admit water into the screen when the photometer is submerged.

The photometer case is attached to one end of a short bar and is balanced by a counterpoise at the opposite end. The operating mechanism consists of a ratchet wheel fastened to the movable photometer and a pawl attached to the horizontal spindle. By pulling a cord the pawl is lifted and the wheel turned until the pawl engages the next tooth. When the operating-cord is released the photometer is steadily fixed in its position. The toothed wheel is spaced for successive adjustment to the following vertical angles: 0°, 10°, 20°, 30°, 45°, 60°, 90°, and 180°.

At both ends the horizontal spindle is supplied with a guide, through which runs a wire. The wires, kept tight with heavy weights, define the aximuthal angle of the photometer. The photometer suspension is movable upwards and downwards, in addition to which the whole bifilar arrangement can be turned and orientated to any azimuthal angle.

The outfit was mounted at the stern o »Albatross» (Fig. 34). The ship was kept the sun athwart. As intensities are symme to a vertical plane through the sun, it not necessary to direct the photometer tow the ship, and thus the disturbing effe its shadow was avoided in the measure

Ratio of Upward to Downward Illumin

Because of scattering in the sea the day is not concentrated only in the directio refracted rays sun from and sky but is d buted over all angles. Roughness of the surface to some degree increases the pre of oblique rays entering the water. production of upwardly travelling light mere scattering effect. A first step in stud the distribution of daylight is to determin upwardly scattered component U (Fig. Some spectral energy curves for the photo directed downwards are shown in Figs. 36 The maximum value of U occurs at 450 mμ, thus shifted towards shorter w lengths from the transmission maximu 470 mμ. This deviation was anticipate Poole (1945) and is caused by sele scattering which increases rapidly toward shorter wave-lengths.

Fig. 35. The spectral photometer is ready for me the upwardly scattered daylight.

nen the distribution of daylight in the sea udied, generally the ratio U/V of the rd to the downward illumination is mined. By means of the directional ometer the ratio U/V was found for red, and near ultra-violet (Table 11). In ion it was studied in blue and in near -violet with the aid of the small photo- r and in the anti-rachitic region with the photometer (Tables 12, 13, 14). Measure- s by means of the spectral photometer ded complete analysis of U/V throughout whole spectrum (Table 15). It has been ed out (POOLE, 1945) that measuring the ard component of daylight falling on the glass of an ordinary photometer directed wards causes the most oblique rays, h are the most intense, to be undervalued. efore, the first set of observations conducted the directional photometer supplies the accurate data. Another objection concerns use of broad filters. For instance, the red RG1 transmits a longer-wave radiation ne downward illumination V than of the ard illumination U. For the combinations +BG12 and UG1+BG12, and for the UVB the shift of the centre of gravity is, ever, inconsiderable.

ne remarkable feature in U/V as presented ables 12—15 is that values for ultra-violet 75 mμ are as high as those for blue at mμ. This is the case at all stations except ion 180, which is characterized by turbid r. For the anti-rachitic radiation the U/V attains a value of at most 4 %, but much lower in turbid-water Station 179 180. It is clear from Table 15 that the imum in U/V ranging from 5 to 7 % for solar altitudes occurs at about 425 mμ, ently irrespective of depth down to 50 m. 470 mμ, to which ocean water is most sparent, U/V is only 4—5.5 %. As we seen, the deviation between U/V maximum transmission maximum is attributed to tive scattering. From values having refe-

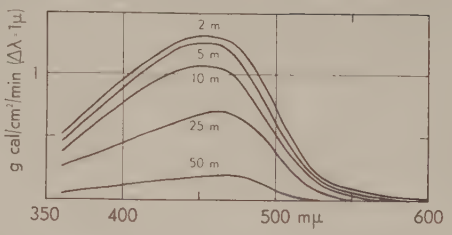


Fig. 36. Spectral energy of the upward illumination. Station 142.

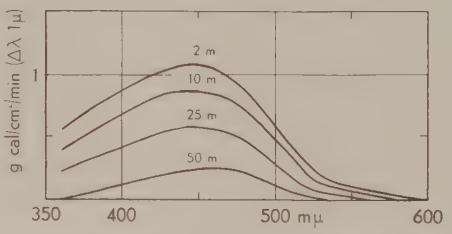


Fig. 37. Spectral energy of the upward illumination. Station 192.

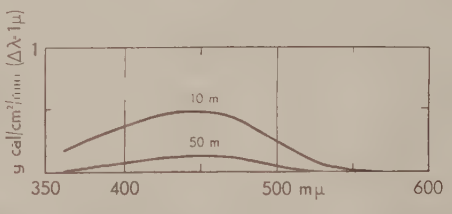


Fig. 38. Spectral energy of the upward illumination. Station 193.

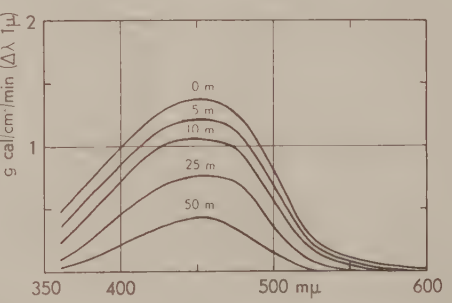


Fig. 39. Spectral energy of the upward illumination. Station 277.

TABLE 11. The ratio of upward to downward illumination U/V determined by the directional photometer in the Mediterranean.

Colour	Depth m	Solar altitude	U/V %
Red (RG1)	5	70°	1
Blue (GG5+BG12)	5	70°	5
Ultra-violet (UG1+BG12)	5	70°	6

TABLE 12. The ratio of upward to downward illumination U/V for 465 mμ and with a high solar altitude.

Depth m	Station					
	141	156	165	180	187	372
0	3.5 %	3.4 %	3.1 %	2.3 %	3.7 %	4.7 %
2	3.2			2.3		
5	3.1	3.4	3.3	2.4	3.6	
10	3.2	3.4	3.3		3.7	5.3
20	2.7		2.5		3.4	
25						5.0
30					3.2	
50						4.7
75						4.1
100						3.5

TABLE 13. The ratio of upward to downward illumination U/V for 375 mμ and with a high solar altitude.

Depth m	Station				
	151	156	165	179	180
0	5.7 %	5.2 %	4.2 %	2.6 %	1.7 %
2					2.0
5	6.6	4.8	4.2	2.5	
10	6.8	5.3	4.2	2.4	
15			3.5		

TABLE 14. The ratio of upward to downward illumination U/V for 310 mμ and with a high solar altitude.

Depth m	Station			
	156	165	179	180
0	3.5 %	2.5 %	1.0 %	0.9 %
2				1.1
5	3.7	2.2	0.7	
10	4.1	1.7		

TABLE 15. The ratio of upward to downward illumination U/V (percent) as determined by the spectral photometer.

Station	Solar altitude	Depth m	Wave-length mμ							
			375	400	425	450	475	500	525	550
191	31°	10	7.5	8.3	9.1	7.0	6.0	4.0	1.6	
192		50	6.9	9.4	10.0	8.3	7.1	3.7		
193	80°	2	5.5	5.8	5.8	5.2	4.1	2.6	1.3	0.6
		10	5.8	5.9	6.1	5.2	4.4	2.9	1.4	0.8
		25	6.1	5.5	6.5	5.4	4.5	2.9	1.4	
		50	4.1	4.4	5.2	4.6	4.1	3.2		
277	74°	0	5.2	6.2	6.9	6.4	5.4	3.1	1.2	0.6
		10	4.8	5.9	6.7	5.9	5.0	3.2	1.3	0.5
		25	4.8	6.1	6.4	5.6	5.0	3.1	1.2	
		50				6.4	5.0	3.2		

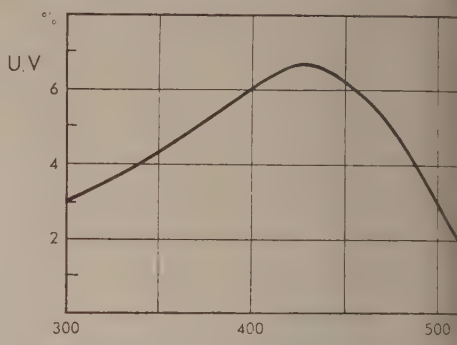


Fig. 40. Ratio of upward to downward illu U/V % for different wave-lengths in clearest ocea

rence to high solar altitudes and gi Table 15 mean values of U/V have been out for different wave-lengths. A pict the trend of the U/V curve is given in F The question of the upwardly scatterin is closely connected with the colour of which is to be discussed later.

It is noted that for the green and t the ratio U/V comes out lower for ocea for coastal waters. (Table 16, 17). In ranges the molecular scattering is not imp Thus, the ocean is rather poor in sca long waves in consequence of its low c of particles as compared with the abu of such in coastal waters.

Finally, it is often observed (Saubel Ruttner, 1941) that the U/V ratio is for low than for high solar altitude ow the more intense upward scattering direct sun rays are rather oblique.

TABLE 16. The ratio of upward to downward i tion U/V determined by the directional photor the Baltic and the Skagerrak.

Colour	Depth m	Solar altitude	Number of observations
Green (VG9)	5—10	20°	6
	5—40	50°	6
	2	overcast	1
Red (RG1)	5—15	50°	2
Blue (BG12)	5—15	50°	2

: 17. The ratio of upward to downward illumina- V determined in the Baltic and the Skagerrak.

lour	Depth m	Solar altitude	U/V %
	0—20	20°	2.5
μ	0—20	35°	1.8
	0—30	50°	1.7

rated in Table 15 for the adjacent Stations 192, and 193 in the Indian Ocean, the s of which have reference to practically same water. With the sun at 31° the ntage of upwardly scattered light reaches 10 %. It is not surprising that the ase stated is most marked for the U/V ium round 425 mμ. As a comparison it own in Table 17 that U/V for green light und by numerous observations in Swedish rs is also affected by solar altitude.

of Horizontal to Downward Illumination

sides observations on the upwardly scat- light a study of the horizontal component gives some information about the angular bution of daylight in the sea. In particu- ATKINS and POOLE (1940) with their cubic- notometer have made a careful study of atio H/V of the »total horizontal compo- to the vertical component, the former as ded with a vertical cylindrical surface. rding to this definition, H/V also means nean value of the tangent of obliquity. ne homogenous water off Plymouth they ned H/V values varying between 73 and , evidently irrespective of the state of ea and of the solar altitude. Nor did they any evidence in favour of a decrease in nean obliquity with increase in depth.

suspending the ordinary small photo- r in a vertical position, so that the receiv- opal glass is vertical, and causing it to e, we could record maximum and mini- values of the horizontal intensity. In the asso Sea some attempts were made to determine H/V by means of a rotating photometer provided with a blue filter (GG5+ BG12) having a centre at 465 mμ, or the same colour for which the daylight transmission is greatest. The method is not credited with a high accuracy but may be useful if due precautions are taken. The photometer must be heavily loaded and the ship carefully handled so that the wire to which the photometer is suspended keeps vertical.

The total horizontal component is approximately computed as the mean value of H_{max} and H_{min} multiplied by π. Judging from the results (Table 18), there is no outstanding change of the average obliquity with increase of depth, though the obliquity is somewhat higher above than below 100 m. The ratio H_{max} H_{min}, however, shows a definite tendency to decrease toward greater depths (Fig. 41). The approach of this ratio to the limiting value 1 is naturally an asymptotic process, but it could be estimated that at 300 m H_{max} and H_{min} are not far from being equal.

More reliable data, though only for small depths, are furnished by the directional photometer. They are collected in Table 19 and are here considered in connection with values derived from JERLOV and LILJEQUIST's measurements (Table 20). The following features are noticed.

TABLE 18. The change of the ratio of horizontal to downward illumination H/V, and of the ratio H_{max} H_{min} for 465 mμ, with a high solar altitude.

Station	Depth mμ	H_{max}/H_{min}	H/V %	Mean obliquity
372	10	3.9	58	30°
	25	3.7	65	33°
	50	2.9	74	36°
	75	2.6	73	36°
	100	2.4	71	35°
374	25	3.3	77	38°
	50	2.4	69	35°
	75	3.1	63	32°
	100	2.2	65	33°
	125	2.1	59	31°
	150	1.6	59	31°
	175	1.7	56	29°

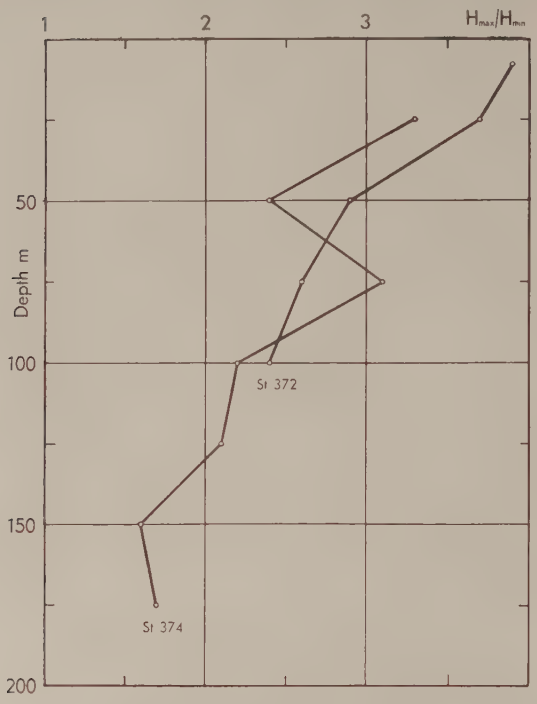


Fig. 41. Decrease of H_{max}/H_{min} with increasing depth. H_{max} is the horizontal component of subsurface light towards the sun, H_{min} that of the opposite direction. Solar altitude 65°

In Swedish waters, valus of H/V for green light in the surface stratum are little affected by the solar altitude. In these areas the high scattering of the green against particles produces very oblique rays, which enter the horizontal component. In the clear Mediterranean water, where particles are few, the molecular scattering is important and causes a high mean obliquity of the short-wave light. But scattering is low for the red and therefore the intensity is largley concentrated to the direction of refracted sun rays (15°).

The average obliquity is governed by a balance between the opposing effects of absorption and scattering, one decreasing and the other increasing it (Poole, 1945). A maximum in average obliquity and therefore in H/V is expected to occur in the green for the green Swedish waters and in the blue for the blue Mediterranenan water. The collected data indicate that this is the case.

With an overcast sky a H/V value of 68 ' obtained in the Baltic. Poole found the cally 73 % just below a calm surface illumi by a uniform overcast sky, in agreement his actual measurements at various d In Poole's opinion this value seems close to the equilibrium value reached ir water. It lends support to this view th 30 and 40 m in the Baltic a similar va 65 % is derived. The equilibrium val H/V is evidently as high as that in green v with their high content of particles. Fo light in clear ocean water a somewhat s value of H/V and hence of the average obl may be accepted. One recalls that belo m in the Sargasso Sea H/V for the blu determined at 58 % (Table 18). It is noting that — on studying residual da at 400 m by means of the deep-sea cam a probable limiting value of 60 % was f According to Poole, an equilibrium of $H/V = 60$ % occurs when the rat scattering to extinction of daylight about 30 %. Then the value of U/V am

TABLE 19. The ratio of horizontal to downwa mination H/V, determined by the directional phot in the Mediterranean.

Colour	Depth m	Solar altitude	H/V %	Me obliq
Red	5	70°	33	18
Blue	5	70°	63	32
Ultra-violet	5	70°	57	30

TABLE 20. The ratio of horizontal to downwar mination H/V, determined by the directional phot in the Baltic and the Skagerrak.

Colour	Depth m	Solar altitude	Number of observations	H/V %	M obli
Green	5—10	20°	6	90	4
	5—15	50°	4	84	4
	30—40	50°	2	65	3
	2	overcast	1	68	3
Red	5—15	50°	2	70	3
Blue	5—15	50°	2	73	3

, which is near the experimental values range 0—50 m (Table 18). For deeper however, there are indications of lower alues.

Angular Distribution and Depth

study of the upward and the horizontal nent has given definite hints about the r distribution of light in the sea. Before g at any conclusions we have to er the direct information yielded by the onal measurements which afford com- polar diagrams of the illumination at any The strongly directed character of the ght at 5 m in the Mediterranean is well ated in Fig. 42. As a comparison ms for 5 m and for 15 m in the Baltic so given (Fig. 43)[1]). They demonstrate with increase of depth, the curves grow rely in breadth and the vertical intensity reased. For scattering reasons already the broadest curves appear for green in the Baltic, and for blue light in the ocean.

view of the data presented it is gathered with increasing depth the angular distri- n of submarine daylight approaches an orium pattern irrespective of state of nd solar altitude. There is no reason to e that this pattern would not be sym- cal about a vertical axis. Under the ption of spherical scattering POOLE) deduced that it should be an ellipsoid volution about a vertical axis, the point servation being the lower focus, and that gure of the ellipsoid should be governed ie relation between absorption and scat- g.

m direct experiment it is clear that the ional character of the light is lost slowly. ie clearest ocean waters the decrease of

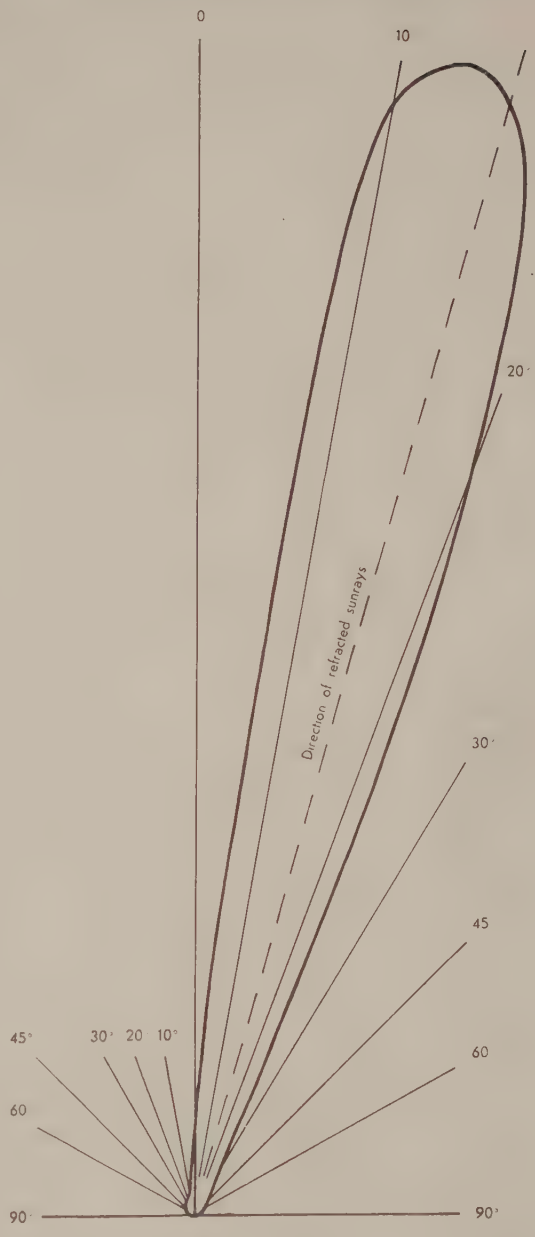


Fig. 42. Light vector diagram in a vertical plane including sun. Depth 5 m in the Mediterranean.

the ratio between maximum and minimum values of the horizontal illumination suggests that the distribution is near its equilibrium at 300 m. The depth at which the limiting state is reached is naturally dependent on the relation between scattering and absorption and is much less in turbid waters.

ost measurements by JERLOV and LILJEQUIST were carried out in the Baltic, not in Norwegian as SAUBERER and RUTTNER (1941) report.

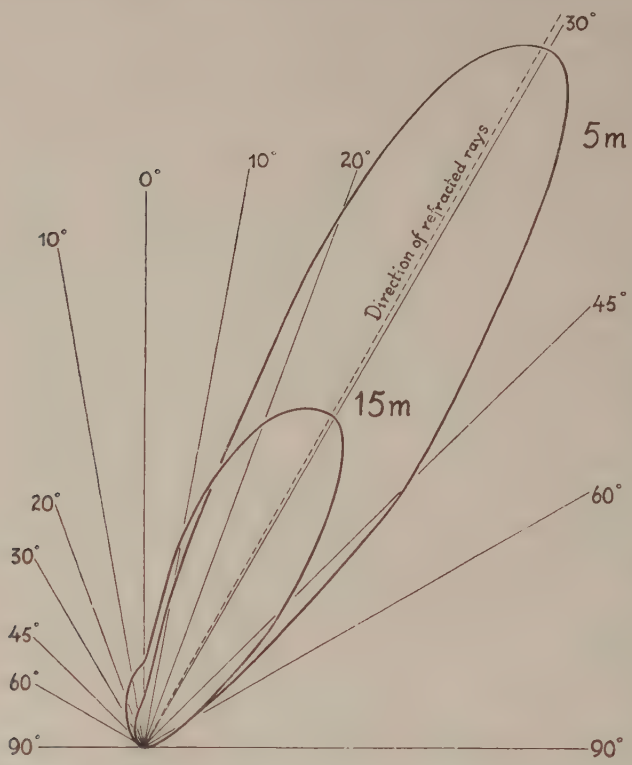


Fig. 43. Light vector diagram in a vertical plane including sun. Depth 5 m and 15 m (curve enlarged 10 times) in the Baltic.

Mean Path Length

As mentioned, the mean path length is defined as the mean value of the path length that light quanta must travel to descend one metre in depth. The mean path length in the upper strata of the sea is subject to certain variations due to the changing distribution of daylight above the water, in the first place low or high solar altitude, and to a slight extent also due to the differing state of the sea surface. In deep water the path length is apparently independent of conditions above the water. The variations spoken of do not affect the measured extinction coefficient very much if the sun is not very low. Some scientists, *e. g.* ATKINS and POOLE, do not pay any regard to the mean path length. As to the decrease of average obliquity from 5 to 40 m in the Baltic (Table 20) the following comment may be added. In this water the vertical extinction coefficient was 0.23 (80 % transm per m depth) at 5 m, and 0.18 (per m depth) at 40 m. With regard accuracy normally attainable w ordinary photometer such small e tions in the extinction coefficient be definitely attributed to a cha the obliquity. In other words, a able alteration of the light distri in the sea does not appear determined extinction coefficient thus far it is not in opposition constancy of the coefficient oft served throughout a series.

The mean path length can be c from the directional measureme the following way. Let E be th flux per steradian emitted in an a imately radial direction by one centimetre of a spherical surface angular zenith distance Θ and a φ. The horizontal surface unit r a total light flux

$$\int\int E \sin \Theta \cos \Theta \, d\Theta \, d\varphi$$

The extinction coefficient per m being get at a point one metre deeper.

$$\int\int E \sin \Theta \cos \Theta \, e^{-\varkappa \sec \Theta} \, d\Theta \, d$$

or, if Θ_m is the zenith distance of the re vector

$$\cos \Theta_m \, e^{-\varkappa \sec \Theta_m} \int\int E \sin \Theta \, d\Theta \, d$$

thus $\sec \Theta_m$ is the mean path length r.

Hence

$$re^{\varkappa r} = \frac{\int\int E \sin \Theta \, d\Theta \, d\varphi}{\int\int E \sin \Theta \cos \Theta \, e^{-\varkappa \sec \Theta} \, d\Theta \, d}$$

The right member is derived by integ from the measurements and then the v r is computed.

The computed values are about 120 all three colours (Table 21). Because high $\varkappa$-value for the red the mean path of red light is higher than the low a

y would account for. These values
e those computed by WHITNEY (1938a),
loes not pay regard to scattering, which
s the mean path length.

e same way, values of the mean path
nder cloudless sky conditions can be
from the measurements made by
and LILJEQUIST. Their observations,
are representative of Swedish areas,
ded off and listed in Table 22 for due
son. Records of the submarine day-
om the extremity of the observation
. Bornö Station have contributed to
g the relationship between mean path
nd solar altitude. It is seen that the
light, to which the water is most
ent, shows a somewhat greater path
than the blue and the red. With an
sky the mean path length is equal
for a cloudless sky at 45 °, as was also
by WHITNEY (1938a).

problem of mean path length in clear
vas studied for all colours on a calm
udless day at Stations 191 and 192 in
lian Ocean. The daylight illumination
was observed by means of the spectral
eter at noon with 80° solar altitude as
in the late afternoon with 30° altitude
23). The extinction coefficient is lower
former than for the latter case, which is
ed to an increase of mean path length
he sun sinks. In the spectrum the
seems to be most marked for the blue
The results indicate that the mean
ngth is to some degree dependent on
ltitude. The experiments conducted
hat at 100 m in the ocean a 30° sun
e only about half of the illumination of
ith sun if illuminations at the water
are put equal. On the other hand, it is
at waves and swell obscure the effect
heights as well as cause variations in
marine daylight. But it may be gathe-
lt day-time in deep water is appreciably
than above the sea.

TABLE 21. Mean path length in the Mediterranean. Solar altitude 70°.

Colour	Mean path length cm
Red	120
Blue	120
Ultra-violet	120

TABLE 22. Mean path length (cm) in the Skagerrak.

Colour	Solar altitude						
	10°	20°	30°	40°	50°	60°	70°
Green	145	140	135	130	125	120	120
Red					120		
Blue					120		

TABLE 23. Percentage of surface radiation at 50 m in the Indian Ocean, and extinction coefficients between 0 and 50 m for two different solar altitudes 30° and 80°.

Wave-length mμ	Percentage of surface radiation at 50 m		Extinction coeff. 0—50 m	
	Altitude 30°	Altitude 80°	Altitude 30°	Altitude 80°
550	3.3	3.5	0.068	0.067
525	5.6	6.9	56	52
500	12.4	15.8	41	37
475	15.8	22.7	37	29
450	16.2	22.7	36	29
425	13.8	20.2	39	31
400	12.3	17.0	41	35
375	8.5	11.2	48	43

The alteration of the angular light distribution with increase in depth is associated with a change of the mean path length, a limit-value being approached. As apparently the average obliquity rapidly tends to a constant value towards greater depths, the same must be the case for the mean path length, its limit-value being probably somewhat lower than 120 cm.

Colour of Ocean Waters

The colour of the sea is a fascinating subject open to observation to anyone ashore or at sea. Since the days of BUNSEN (1847/48) several explanations for the blue colour of the clear ocean water have been advanced. In

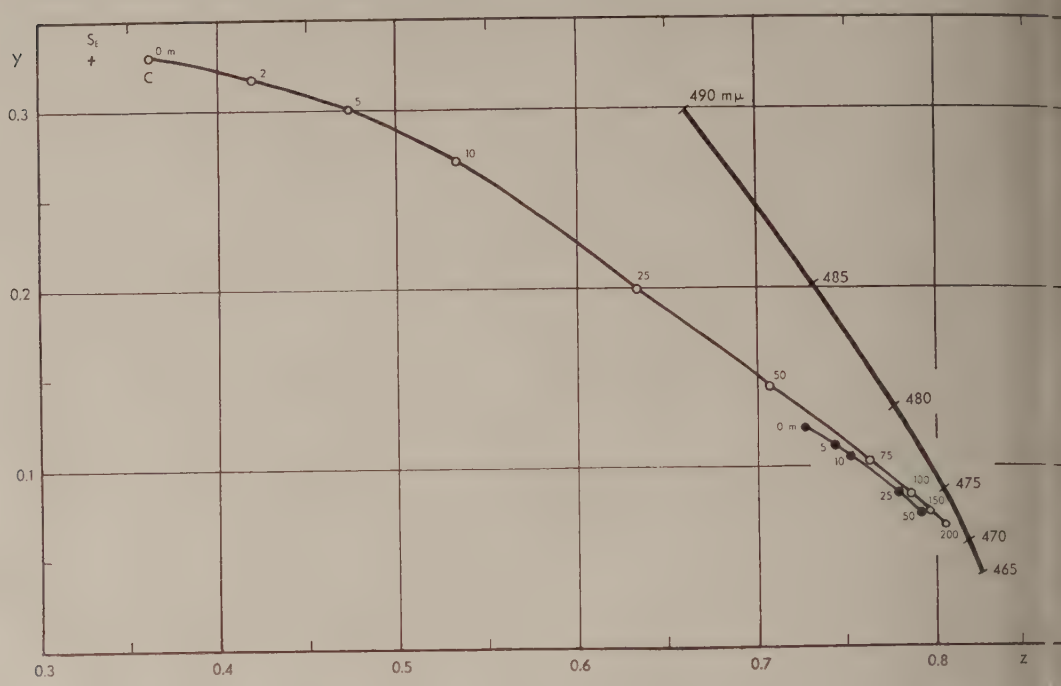


Fig. 44. Chromaticity chart showing locus of spectrum 465—490 m μ, loci for downward illumination (—•—) for upward illumination (—•—) in the clear ocean. S_E is the equal energy stimulus and C represents the quality of illumination above the sea.

the elaborate theory by KALLE (1938) the selective scattering plays an important rôle in the arising of the blue colour. By direct observation KALLE studied the colour in different areas, in particular in the Sargasso Sea, and applied the theory by YOUNG-HELMHOLTZ, as revised by HASCHEK-HAITINGER (1932), to express the colour by a single wave-length.

Reference has already been made to the relation between colour and transparency of sea water. The clearest ocean water is characterized by an intense blue colour. Decreasing transparency runs together with a change of colour toward longer wave-lengths. The main features of the horizontal colour distribution in the Atlantic, as it appears on the chart given by SCHOTT (1926), is consistent with the present measurements of daylight penetration. Some discussion can be raised concerning the position of the boundary of the clear Sargasso water but this, no doubt, fluctuates. The »Albatross» found that Amazon water extends its i as far out as Station 361 and 365 whic however be a temporary occurrence. also be mentioned that the greenish water flowing into the Mediterranea to affect slightly the water colour Tyrrhenian Sea.

During the »Albatross» expedition th of the sea was not a subject for direct However, the spectral energy curves downward and the upward component light yield, free from subjective observa physical expression of the colour. On th mental basis of energy curves for cleare water a colour analysis is made in tern C. I. E. chromaticity chart plotted rel the Y and Z co-ordinates (See WRIGH and the figures marked against the loci the depth in m (Fig. 44). The locus of trum 465—490 mμ is also shown in the C represents the quality of the illumination, while S_E is the equ

s. It is seen that the water locus for
nward component is a bent line, which
the change of dominant wave-length.
t 25 m the upwardly turned human
ll already get a blue impression, the
overing the range 480—450 mμ. The
or the upward component, on the other
s a short and remarkably straight line,
lour changing within the blue from
at 0 m to 470 at 50 m. Both lines,
are very close to each other, seem to
ge to a saturate colour of 467 mμ.
also the wave-length for which the
is most transparent. Thus, the blue
of the clear ocean as observed directly
above is expressed in the wave-length
μ. KALLE using the above-mentioned
ure found in the Sargasso Sea a colour
mμ.

colour of the sea is closely connected
cattering as a funtion of wave-length.
gin with, we confine our interest to the
strata of clear ocean water and discuss
attering in view of all data so far
ted. It has been shown (WHITNEY, 1938;
AND, 1939; POOLE, 1945) that, under the
ption of spherical scattering and no
ole scattering, the scattering coefficient
be expressed by the formula

$$S = \text{constant} \cdot \varkappa \cdot U/V,$$

the constant is dependent on the mean
length. LAUSCHER (1947) has shown that
rmula also is valid for clear water in
multiple scattering occurs.

scattering S is made up of a non-selective
n s and a selective portion s', the latter
caused by the water itself and propor-
to $\lambda^{-4.15}$ (SMOLUCHOWSKY).

$$S = s + s'$$

ng extinction coefficients $\varkappa$ for the first
of m (Table 8), U/V values from Fig. 40,
' values as computed by LE GRAND, we

TABLE 24. Scattering coefficients for the upwardly travelling daylight and percentage of scattering in the extinction.

λ mμ	$\varkappa$ m^{-1}	U/V %	s' m^{-1} Le Grand	s m^{-1}	S m^{-1}	$S/\varkappa$ %
310	0.152	3.2	0.0151	0.0010	0.0161	11
350	63	4.3	89	10	99	16
400	28	6.0	50	10	60	21
450	19	6.2	31	10	41	22
500	28	3.0	20	10	30	11
550	59	0.7	13	10	23	4

obtain a probable non-selective scattering s of 0.0010 (Table 24). This attempt to get an idea of the upward scattering of daylight shows that the percentage of scattering in the extinction is at most 22 %. It is also demonstrated in Table 24 that the non-selective scattering is the minor portion, in the blue about 1/3 of the whole scattering. But the Tyndall measurements reveal that the water contains a certain amount of big particles which produce a non-selective scattering several times higher than the selective scattering. According to KALLE (1939) the explanation of this apparent contradiction is that the selective scattering, contrary to the non-selective, is effected without losses and must therefore predominate. We have also seen that the non-selective scattering is not uniform but produced forward (p. 26), and so must give a small contribution to the upwardly travelling light U. On the other hand, non-selectively scattered light enters the horizontal component of daylight in the sea H to a greater extent. One recalls that for the horizontal component in deep water a limiting value of the percentage of scattering in the extinction was suggested at 30 % (p. 40).

The predominance of selective scattering in the upward component of daylight is well developed in the extremely clear water of the Sargasso Sea and of the East Mediterranean.

But in ocean water of normal transparency

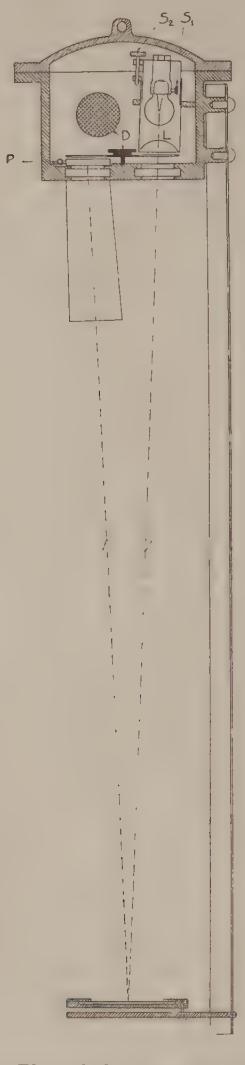


Fig. 45. Plan of the transparency-meter.

where big particles are more abundant, the multiple selective scattering is extinguished by absorption, and the brilliant blue colour is lost.

Transparency of Ocean Waters

It is stated that the transparency-meter with its lightpassage of only 2 m is not a very sensitive device by which to record the small variations in ocean transparency. On the other hand it determines, when standardized, the true extinction by the water, *i. e.* the sum of absorption and scattering. Most results have already been applied in a pr discussion with a view to distinguishing be the absorption portion and the scat portion in the extinction (Table 6).

Transparency-meter

The transparency-meter is the o PETTERSSON apparatus with some te modifications mentioned here. The light- is a lamp with a rectangular filament o mm. It can be centred to the optica of the hemispherical lens L (Fig. 45) l three screws S_1, and can be moved p to the axis by the screw S_2. The whol including the lamp and the lens can be taken out and then replaced and in exactly the same position as before. A ment is performed so that the light produced in air has a diameter at the of about 10 cm, and so that the active s of the photo-cell P receives the whole image of the filament. This has the adv that the contraction of the beam in w of little account, as about the same a of energy from the lamp reaches the pho when readings are taken in air as well optically pure water.

The radiation of the lamp, the curr which is regulated by a resistance, is constant with the aid of a control pho (not visible in Fig. 45) placed 8 cm fro lamp and provided with a 2 mm blue BG12, as the blue part of the lamp-spe is most sensitive to variations of the current. The light from the filament im on the control cell through a hole in the tube, which is arranged so that the ligh just covers the active surface of the cell. Both photo-cells used in the app were selected from a great number of s for their high sensitivity and small effect. The control cell is connected w AEG luxmeter, the cell P with a ligh galvanometer (sensitivity about $2 \cdot 10^{-8}$ res per scale-unit). When readings are

, the windows and the mirror being
cleaned, a certain deflection on the
ter always corresponds to a certain
ion on the galvanometer, *i. e.* when the
current read on the luxmeter is adjusted
gulating the resistance to a definite
oint, the galvanometer is always to
the same deflection. On exchange of
the new lamp is centred so that the
sent out through the window gives a
ar spot concentric to the mirror, after
the mirror is slightly adjusted so that
iage of the filament falls on the photo-
'. By means of the screw S_2 the lamp
ved towards the lens till the light beam
overs the control cell and the desired
pondence between the two galvanometers
ablished.

. 45 also shows an electromagnetic filter-
ing device D, which permits the intro-
n of three colour filters in succession,
RG1, 2 mm VG9 and 2 mm BG12,
screen in front of the lamp. The device,
requires 12 volts, is operated from
oard. The entire device with the electro-
et and the filter disc can be placed in
thdrawn from the case as one unit when
amp-tube is off.

e case always contains a dessicator when
nstrument is lowered into the water in
to avoid moisture on the windows. In
rizontal position the transparency-meter
neasure the transparency within a water
only some 5 cm thick. The corrections
ubmarine daylight to be deducted from
leflection, read at each depth, are found
troducing the opaque screen in front of
amp.

e transparency-meter measures the trans-
icy within three spectral blocks. The
curves are shown in Fig. 46. The ranges
a tenth of maximum height), and the
es of gravity when the instrument is in
are given in Table 25. They are very
affected by the lamp-emission, and so

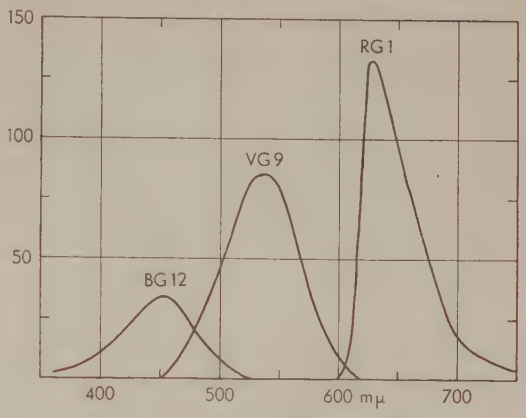


Fig. 46. Filter curves for the transparency-meter.

the lamp-current need not necessarily be the same from one measurement to another. When the transparency-meter is in ocean water, the filter-centres are slightly shifted as is also shown in Table 25.

The standardization of the instrument was performed in the following way. The water to be investigated was poured into an earthenware cylinder of such a height that the transparency-meter could be immersed in a vertical position. In this way waters of different transparency were studied. A sample of each was placed in a Pulfrich photometer and its spectral extinction compared with that of double-distilled water, for which CLARKE and JAMES' (1939) extinction values were used. The optics of the transparency-meter can be adjusted so that the standardization remains permanent and can also be reproduced when lamps are exchanged. The relation u_w/u_a is essential for obtaining the transmission value, u_w being the deflection on the galvanometer when the transparency-meter is in water, u_a

TABLE 25. Filter data for the transparency-meter.

Filter	Range mμ	Centre of gravity mμ	
		In air	In water
RG 1	605—705	650	655
VG 9	470—600	535	540
BG 12	380—510	445	440

TABLE 26. Standardization data for the transparency-meter. Transmissions (percent) per m are computed from the ratio u_w/u_a, u_w being the deflection on the galvanometer when the transparency-meter is in water, u_a the deflection in air.

RG 1 655 mμ	VG 9 540 mμ	BG 12 440 mμ
$1.07\sqrt{u_w/u_a}$	$0.94\sqrt{u_w/u_a}$	$0.91\sqrt{u_w/u_a}$

the deflection in air. The conclusive standardization data valid for water of different transparency are given in Table 26.

To begin with, the transparency-meter was lowered at the stern of the »Albatross» (Fig. 47) and was suspended to the 600 m cable of the winch, this cable also being designed for daylight measurement. As it was found to be of little interest to extend measurements lower than 100 m, the transparency-meter was later suspended to the hydrographical wire.

Results

The sparse material of transparency measurements is summarized in Table 27. It comprises one series of observations from the Carribean Sea, one from the Panama Golf, one from the area south of Galapagos, the above-mentioned

Fig. 47. The transparency-meter is in action.

series of four stations across the equat currents, and finally in the Atlantic measurement from the Romanche Deep one from the Sargasso Sea.

The first three series are made for all t colours. They have already been discusse connexion with daylight measurements (T 6) but also have an interest of their own comparison with the investigation by CL and JAMES (1939) reveals that their t mission values for shaken sea water from Continental Slope, Station B, Sample 7 similar to those found at our Station Though transmissions for water at this St 29 are lower than for double-distilled w (Table 28), the ratio between transmissio blue and transmission to red is nearly same as for double-distilled water. This l support to the statement that the actio contaminations in the water is only sli selective. On the other hand, Statio representing the turbid water at the Galap shows a lower ratio, chiefly because o high amount of yellow substance (p. 28

As variations in transparency are marked for blue than for red light, transparency-meter was used in the subsec work only with the blue filter. At first section across the equatorial currents is c dered. Unfortunately Station 123 could be made according to plan at the nor boundary of the counter-current but delayed to 15°N. Mean values of transmis at 1, 25, 50, and 75 m for the four sta are given in Table 29. There is an ob tendency to lower transparency in the S Equatorial Current and in the equator c gence than in the Counter-current and North Equatorial Current. This is consi with data from the Tyndall measuren which prove that particles are more abu in the former than in the latter area. is also referable to Station 107 and 111 in this respect in the extension of Galap water.

E 27. Transmission values per m obtained by means of the transparency-meter.

ation	Depth m	Transmission per m		
		655 mμ	540 mμ	440 mμ
29	2	69 %	86 %	88 %
	5	69	86	88
	10	69	89	88
	25	70	89	92
46	1	67	80	84
	50	68	80	80
53	1	64	75	76
	25	65	75	76
	50	64	76	80
	75	67	79	82
	100	64	76	75
107	1			89
	10			89
	20			89
	30			90
	40			90
	50			91
	60			92
	70			93
	80			93
111	2			90
	25			90
	50			91
	75			92
117	1			92
	25			92
	50			93
	75			91
	100			93
123	1			92
	25			92
	50			92
	75			91
	100			90
340	2			87
	25			88
	50			94
371	1			93
	25			93
	50			92
	75			93
	100			93

hese measurements — as well as the light measurements — prove that variations ocean transparency are as a rule small. en an island in the ocean was being roached it was observed that an obvious amination actually appears only in the close proximity of land. Conditions are naturally different off big islands, for instance in Indonesia, particularly near the mouths of rivers. But even in these cases the water clears up very rapidly on its way out from the island toward the ocean. As regards this, reference is made to the Tyndall measurements at the mouth of the Nile, which shows that the great amount of sediment carried by the Nile flocculates rapidly. The water is already very clear some sea-miles out in the Mediterranean.

For the Atlantic two measurements are at hand. The surface water at Station 340, the Romanche Deep, is relatively turbid conformably with the high content of yellow substance found there (p. 28), whereas the pure water of the Sargasso Sea shows the highest clarity found in natural waters.

The change of transparency with depth is inconsiderable, as demonstrated in Table 27. In some cases, *e. g.* Station 107, there is a slight increase of transparency with increase of depth corresponding with the distribution of particles, but for the rest the great changes in quantity of particles with depth are not revealed in the transparency measurements.

TABLE 28. The selectivity of extinction by ocean water.

mμ	Double-distilled water Clarke a. James		Station 29 2—25 m		Station 53 1—100 m	
	Transm. per m	Relation	Transm. per m	Relation	Transm. per m	Relation
655	74.0 %	1	69 %	1	65 %	1
540	93.5	1.26	87	1.26	76	1.17
440	97.8	1.32	89	1.29	78	1.20

TABLE 29. Transparency section across the equatorial currents in the Pacific.

Station		Transmission per m for the range 0—75 m
107	South Equatorial Current	90.6 %
111	South Equatorial Current at the Equator	90.7
117	Equatorial Counter-current	92.0
123	North Equatorial Current	91.7

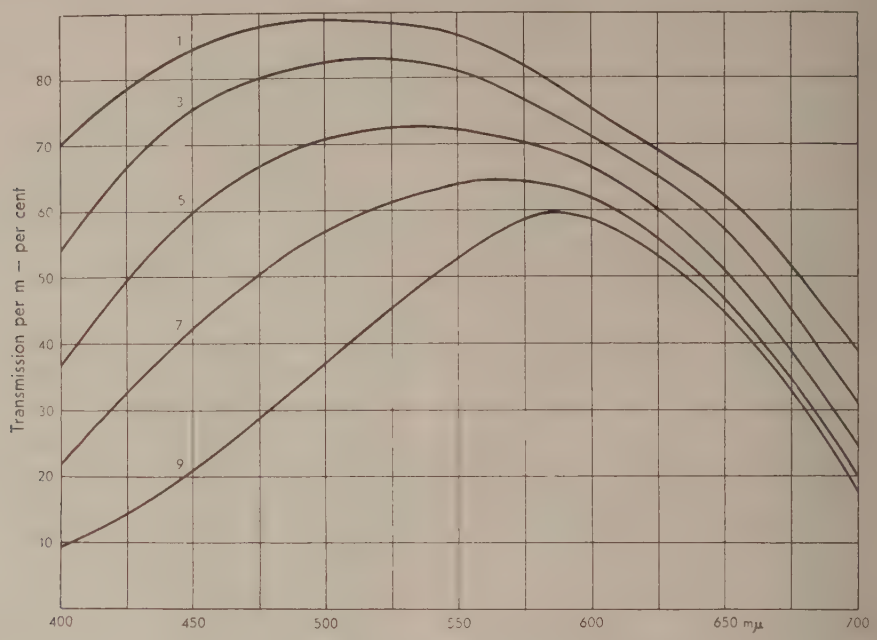


Fig. 48. Normal transmission curves for different types of coastal water. Solar altitude 45°. (Jerlov and Kullenl

Nevertheless, by employing a great number of transparency observations it is possible to get reliable data for a standardization of the Tyndall measurements.

The highest transparency to the blue was determined at a value of 93 %, which compares well with the corresponding value for double-distilled water of about 98 %. The difference is mainly attributed to the scattering effect of particles. In deep water which is poor in particles the transparency could attain a value as high as 97 %, approaching the transmission for double-distilled water.

Classification of Sea Water

It may be worth while to ascertain whether the mechanism by which the transparency of the sea is decreased conforms to law. Jerlov and Kullenberg (1946) have already made an attempt to deal with this problem and propounded a series of normal transmission curves for the sea. Lacking data for clear ocean water, they used transmission values for double-distilled water. The »Albatross» measurements yield adequate information ab the optical qualities of ocean water, and we had better leave out curves given by th authors for very high transparency and con their schema to transmissions occurring coastal areas. The schema is based on exp ments from the Baltic, the Skagerrak, Gullmarfjord, Norwegian fjords, and from North-American Pacific coast; in short may be considered as characteristic of coa water in the temperate zone. It is appropr

TABLE 30. Normal transmission values (percent) p for coastal waters and with the sun at an altitude of (Jerlov and Kullenberg).

Type of coastal water	Wave-length mμ					
	400	450	500	550	600	650
1	70.0	84.6	88.6	86.9	75.4	62.8
2	64.5	81.8	86.5	85.0	74.1	61.1
3	54.1	75.5	82.1	81.1	71.6	57.7
4	45.0	68.4	76.9	76.8	69.4	54.6
5	36.6	60.5	71.1	72.4	67.1	51.9
6	29.0	51.7	64.1	68.1	64.8	49.4
7	21.8	42.3	56.5	63.6	62.6	47.4
8	15.2	32.3	47.6	58.3	60.8	46.0
9	9.7	21.7	37.5	53.5	59.0	45.2

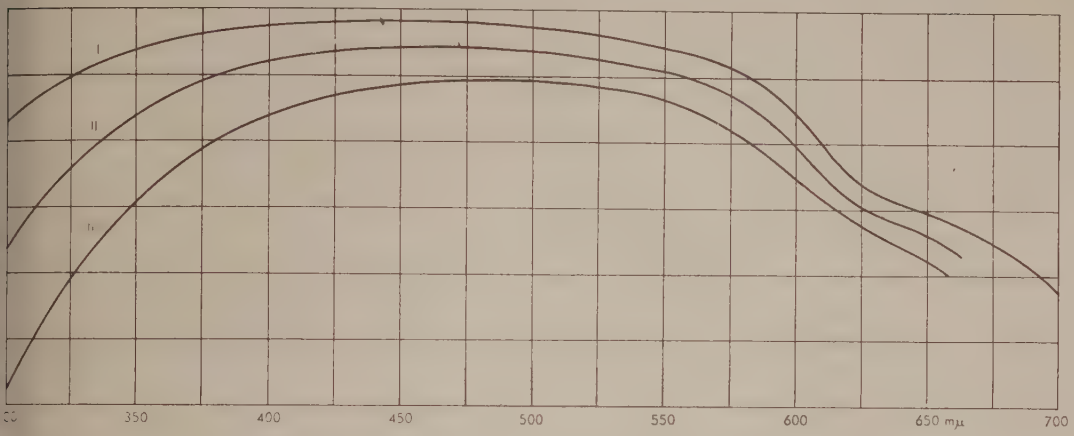


Fig. 49. Normal transmission curves for different types of ocean water. Zenith-sun.

hoose a solar altitude of 45° when comput- the transmissions. These are given in le 30, and some of the corresponding normal ismission curves (for mean transmissions ween 388 and 712 mμ of 35, 45, 55, 65, 72.5 %) are demonstrated in Fig. 48. selective action of yellow substance, ch is abundant in these waters, is clearly ibited in these curves. It has already been strated in this work how, for the same son, the corresponding ultra-violet curves off towards short wave-lengths.

'he optical conditions of ocean water, which y little, ought to be still more easily sified. We have seen, it is true, that a ying part of the extinction by turbid ocean er is due to yellow substance, but this gularity is not proved to be of any great portance. The red and the ultra-violet not ng measured much lower than 10 m, we e to confine the treatment to the surface was also done for coastal water.

Thus, the collected material is treated with the view of computing normal transmission values (Table 31)). Fig. 49 shows conclusive curves for the visible range, to which the short-wave curves, as derived from the ultra-violet measurements, are connected. The values are considered to be valid for a zenith sun. The uppermost curve (Curve I) is applicable to the clearest ocean water encountered, whereas Curve II is characteristic of ocean water of relatively high turbidity. This curve satisfies conditions at so different localities as the Red Sea and the Kapingamarangi atoll. In fact, transmissions for all stations of optical measurements are between these two limiting curves I and II with the exception only of those found for the Galapagos region and for the Madura Strait. Using in the first place ATKIN's and POOLE's (1937) data from the Channel and the ultra-violet measurements at Madura, secondly transparency measurements at Galapagos, and with some

TABLE 31. Normal transmission values (percent) per m for ocean waters and with the sun at zenith.

ype of ocean water	Wave-length mμ														
	310	375	400	425	450	475	500	525	550	575	600	625	650	675	700
I	86	96.3	97.2	97.8	98.1	98.2	97.2	96.1	94.2	92	85	74	70	65	58
II	69	89	92	93.5	94	94	93.5	92.5	90.5	87.5	80	71	67		
III	50	79	84	87	88.5	89	89	88.5	86.5	82.5	75	68	63		

regard to the observations of long-wave light penetration made by UTTERBACK (1936) in the North Pacific Ocean, Curve III is derived. Though it is flat, the maximum of Curve III is slightly shifted toward long wave-lengths as compared with Curve II. In the greater part of the spectrum the trend of the curve almost agrees with the highest curve for coastal waters, but a difference appears at short wave-lengths, which are more rapidly extinguished in coastal water due to its higher content of yellow substance.

The three curves presented account for the rate of transmission of daylight in the uppermost 10 m stratum of ocean water. They represent the tropical and subtropical areas of the oceans, while the northern regions or at least their arctic portions are likely to exhibit even more turbid water. It is a salient feature that in the ocean the increase of extinction is a selective process, the short-wave part of the spectrum being relatively more reduced than the long-wave part. But the selectivity, chiefly due to yellow substance, is not by far so well developed as in coastal waters.

Total Radiation in the Sea

The spectral energy curves founded on measurements in the range 350—700 mμ also yield information about the total radiant energy from sun and sky incident on horizontal surface. But it is necessary extrapolate at both ends the surface cu (0 m) with the aid of available data. T total radiation at the various levels in the is found simply by computing the area enclo between the spectral curve and the base li

Table 32 is prepared to give the percent of total incident energy reaching differ depths in different types of ocean water (N I, II, III) and of coastal water (Nos. 1, 3 7, 9), as they are already classified. It be recalled that the sun is assumed to be zenith for ocean waters and at an altitude 45° for coastal waters. The radiation pe trating the water surface with the sun at zer and with a clear sky is supposed to be 100 g cm²/hour (SVERDRUP, JOHNSON and FLEMI p. 776, 1946). With a solar altitude of 45° corresponding supply of energy is approxi tely 70 gcal/cm²/hour.

Extinction coefficients per m have b computed for the different depth interval the three types of ocean water as well a the five types of coastal water (Table The reduction of the total incident en with increase of depth is also illustrated Figs. 50 and 51. The characteristic ben of the logarithmic curves for clearest o water is also apparent, though obscured the total radiation.

TABLE 32. Percentage amounts of total incident energy from sun and sky (see Tables 30 and 31).

Depth m	Oceanic water			Coastal water				
	I	II	III	1	3	5	7	9
0	100	100	100	100	100	100	100	100
1	44.5	42.0	39.4	36.9	33.0	27.8	22.6	17.6
2	38.5	34.7	30.3	27.1	22.5	16.4	11.3	7.5
5	30.2	23.4	16.8	14.2	9.3	4.6	2.1	1.0
10	22.2	14.2	7.6	5.9	2.7	0.69	0.17	0.05
20				1.3	0.29	0.020	0.0016	0.00
25	13.2	4.2	0.97					
50	5.3	0.70	0.041	0.022	0.00059			
75	1.68	0.124	0.0018	0.00057				
100	0.53	0.0228						
150	0.056	0.00080						
200	0.0062							

TABLE 33. Extinction coefficents of total incident energy from sun and sky (see Tables 30 and 31).

Interval of depth m	Ocean water			Coastal water				
	I	II	III	1	3	5	7	9
0—1	0.82	0.88	0.94	1.00	1.12	1.32	1.52	1.75
1—2	.145	.199	.262	0.307	0.390	0.53	0.69	0.85
2—5	.080	.130	.196	.215	.292	.43	.56	.67
5—10	.052	.101	.159	.174	.248	.38	.50	.59
10—20				.150	.223	.35	.47	.55
10—25	.035	.080	.137					
20—50				.136	.206			
25—50	.037	.072	.127					
50—75	.046	.069	.124					
75 100	.046	.068						
100 150	.045	.067						
150 200	.044							

Values of the total incident energy presented ce may be useful for finding the greatest pth at which photo-synthesis can take place. particular, conditions in the South Sea are eresting with regard to reef-producing corals. ie radiant energy together with warm and saline water is one of the requirements of the reef-building organisms. In transparency the South Sea equals the clearest ocean water, and the supply of energy is as given in the first column in Table 32.

However, for biological purpose it is impor-

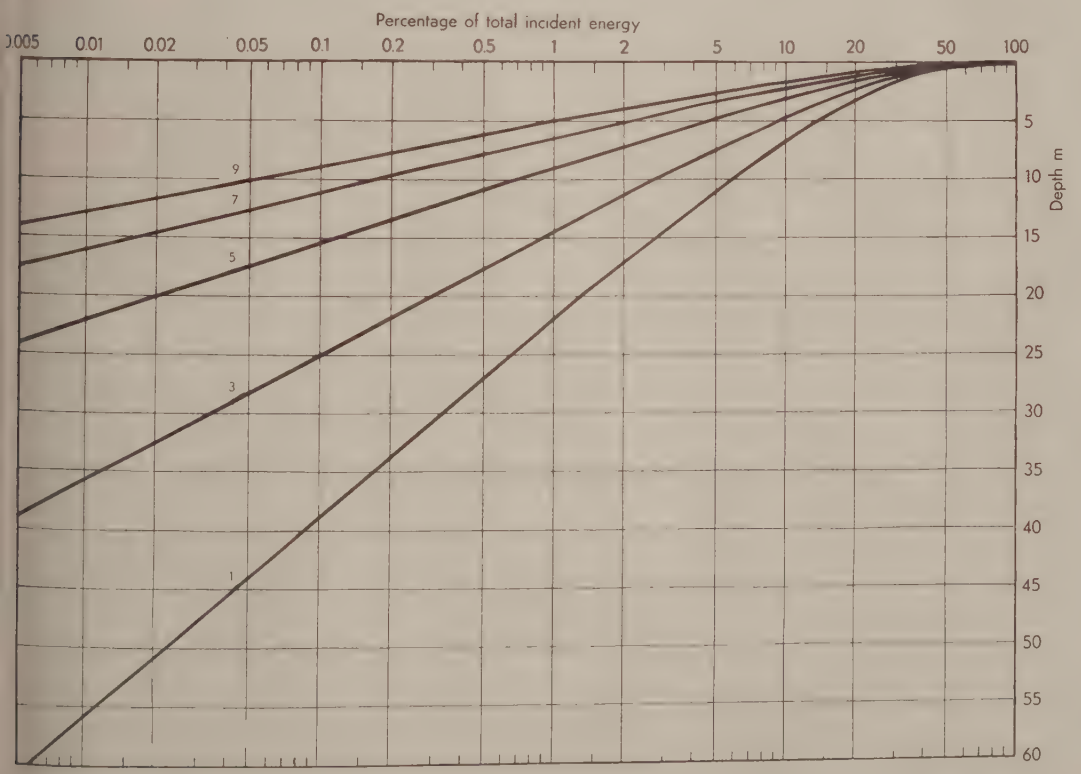


Fig. 50. Percentage of total incident daylight energy at different depths in different types of coastal water.

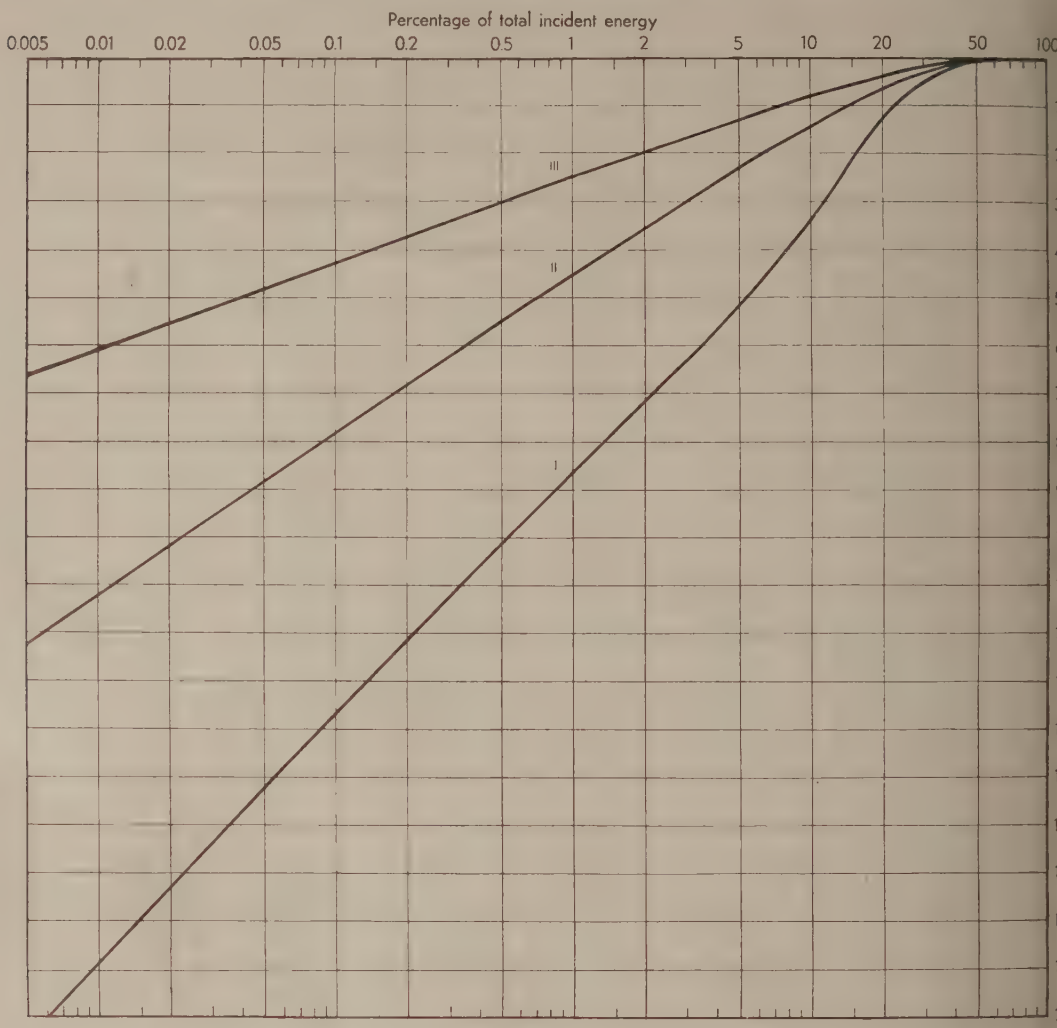


Fig. 51. Percentage of total incident daylight energy at different depths in different types of ocean water. Zenith-

tant to know the total light flux rather than its vertical component. For instance, an organism suspended in the water receives radiation from all direction. JERLOV and LILJEQUIST (1938) have treated this problem and by experiment found that values of vertical illumination in coastal waters should be increased by 30 % in order to include the energy from all directions. From measurements of the angular distribution of daylight in the Mediterranean (p. 41) it may be inferred that in ocean water with a high solar altitude such an increase of 20 % is probable for all depths.

Summary of Principal Results

The penetration and distribution of subs face radiation from sun and sky has b studied in tropical and subtropical areas of oceans by means of various photometers.

The results appear primarily as spect energy curves for the downward illuminat as received on a horizontal surface in the oce the energy being given in gcal/cm²min (spect interval = 1 μ). In clear ocean water the l waves are more rapidly extinguished with crease of depth than are the short waves a so a salient asymmetry of the spectral cu

eveloped, its maximum being at about
mμ (Fig. 13). On the other hand, for a
turbid water the lower curves are essenti-
symmetrical at approximately 475 mμ
8). It is demonstrated how the energy
e contracts with increasing depth, the re-
l blue daylight at 200 m being practically
in the narrow range 430—500 mμ (Fig. 16).
ie spectral measurements also are present-
rom another point of view; logarithmic
s for every 25 mμ show the percentage
urface radiation that reaches the various
hs. For short-wave daylight in clear water
trend of the logarithmic curves exhibits
aracteristic bending, the light being less
ced in the upper than in the deeper strata
. 20). The fact that the vertical intensity
aylight does not, in the upper layers, fall
vith increasing depth according to a simple
nential law is attributed to scattering
ts (Le Grand, 1939).

survey of the transparency to the most
etrant blue daylight in various ocean areas
iven and features in the horizontal varia-
of transparency are discussed (p. 20). In
icular, a relatively low penetration was
erved in the upwelling areas west of South
erica and of Africa, whereas extremely clear
er was encountered in the Sargasso Sea
the East Mediterranean.

pecial measurements of the short-wave ra-
ion have revealed that the penetration of
ultra-violet at 310 mμ, *i. e.* UVB or an-
hitic ultra-violet, in the clearest ocean
er is as high as 86 % per m depth. The
gical importance of this high transparency
uch higher than previously supposed — is
ussed. Normal transmission values for
t-wave radiation in the ocean are given
he upper set of curves in Fig. 33. A com-
son with the lower set of curves, derived
measurements at Bornö Station, shows
ndamental difference, largely due to the
er content in coastal water of the dissolved
low substance».

The average obliquity of the submarine daylight has been studied at different solar altitudes in ocean as well as in coastal water. It is governed by a balance between the opposing effects of absorption and scattering, one decreasing and the other increasing the obliquity (Poole, 1945). Maximum in mean obliquity occurs for the most penetrant wavelengths, for the blue in the open ocean and for the green in the Baltic. Naturally the average obliquity is to some degree dependent on solar altitude but its change with depth is not found to be important.

The directional measurements, which afford a complete light-vector diagram of the illumination at any level in the sea, prove the strongly directed character of the light near the surface (Figs. 42 and 43). With increase in depth the curves grow relatively in breadth and the vertical intensity is increased; the angular distribution of daylight approaches an equilibrium pattern symmetrical about a vertical axis and irrespective of the sea state and of the solar altitude. In the clear ocean the distribution is almost at an equilibrium at 300 m. The depth at which the limiting state is reached is dependent on the relationship between scattering and absorption, and is much less in turbid waters.

In accurate light measurements due attention must be paid to the mean path length (Whitney, 1938 a), defined as the mean value of the path length that light quanta must travel to descend one metre in depth. It is demonstrated in Table 23 how the extinction by ocean water is higher at 30° solar altitude than at 80° due to an increase of the mean path length when the sun sinks. Probable values of the mean path length in ocean as well as in coastal waters are derived (Tables 21 and 22).

The true extinction of light by sea water as measured by means of a transparency-meter is the sum of absorption and scattering. In the ocean, scattering by particles predomi-

nates over absorption by particles and dissolved matter. It is found to be only slightly dependent on wave-length which indicates that the size of particles in general exceeds 3 μ.

The extinction of daylight by ocean water is made up of absorption and a *fraction* of the scattering. If it is compared with the true extinction this fraction comes out very small. This suggests that scattering is mainly of forward direction and due to refraction through comparatively large particles. As the extinction of daylight is not much affected by scattering it does not, as a rule, give an indication of the content of particles.

The ratio of upward to downward illumination U/V in the sea gives information about the light scattered upwards. Maximum in U/V occurs at 425 mμ in the clear ocean (Fig. 40) whereas, as we have seen, the transmission maximum is at 470 mμ. The deviation is attributed to selective scattering. It is necessary to distinguish between a selective scattering caused by the water itself and a practically non-selective scattering due to suspended particles. The former is almost equal in all directions and implies no loss of intensity (KALLE, 1939), the latter is largely of forward direction and reduces the intensity. Therefore, in the upwards travelling daylight selective scattering predominates, whereas non-selectively scattered light enters to a greater extent in the horizontal component. In other words, the relationship between selective and non-selective scattering is dependent on direction.

The extinction of daylight in the clearest ocean water is shown in Table 8 and Fig. 28. In the surface stratum it is due mainly to absorption by the water itself. This explains why for wave-lengths 375—425 mμ it is smaller than the extinction by pure sea water (CLARKE and JAMES, 1939) which is made up of absorption *and* scattering.

For illustrating the effect of yellow substance in the ocean (KALLE, 1937) the mean extinction coefficient 0—50 m for blue light is compared at the various stations to the total scatte of blue light as measured by means of a T dall-meter (Fig. 27). Yellow substanc practically absent in the clearest ocean w but in water of normal particle content th is a noticeable production of it. It is obv that upwelling water contains abnorm much yellow substance. Even in the oce divergences there are indications of a hig content, *i. e.* more than particles would acc for. A supply of yellow substance from d layers, where a disintegration of carbo-hydr takes place, is also suggested. At last it m be mentioned that the Red Sea contair brown dissolved component probably due decomposition of red algae.

For the blue colour of the clear ocean s tive scattering plays an important rôle (KA 1938). But in ocean water of normal tr parency, where big particles are more abund the multiple selective scattering is of second importance compared to absorption, and brilliant blue colour disappears.

The spectral energy curves for the d ward and the upward component of dayl yield, free from subjective observation, physical expression of the water colour. this experimental basis a colour analysis been made in terms of the C. I. E. chromat chart (Fig. 44). A human eye looking upw will get a blue impression already at a dep 25 m. The blue colour as observed directly above is expressed in the wave-length 473

An attempts is made to ascertain whe the mechanism by which the transparenc the sea is decreased conforms to a ge law. A series of normal transmission cu earlier propounded (JERLOV and KULLENB 1946) is revised in view of new data an moreover limited to coastal waters (Fig. The selective action mainly from yellow stance, which is abundant in these wate clearly exhibited in the curves.

An attempt also is made to classify c waters in three types for which ATKIN's

E's (1937) observations from the Channel JTTERBACK's (1936) from the North Paci- cean are also used (Fig. 49). The three s presented account for the rate of trans- on of daylight in the uppermost 10 m um of ocean water. The increase of ction in the ocean shows a selectivity, y due to yellow substance, but by far s well developed as in coastal waters.

Figs. 50 and 51 show the percentage of total incident energy reaching different depths in various types of coastal and of ocean water, as here classified. These values of vertical illumination in coastal waters should be increased by 30 % in order to include all the energy irrespective of direction. In ocean water with a high solar altitude a similar increase of 20 % is more correct.

References

S, B., and W. RODHE
2. Über die Milieufaktoren in einigen Südschwedischen Seen. Symb. Bot. Upsal., v. 3.
, G.
7. Über Lichtabsorption von Wasser und Algen in nat. Gewässern. Bergens Mus. Årsbok. Naturw. rekke, 2.
RÖM, A.
7. On the standardization of photoel. cells by means of sun rad. Stat. Met.-Hydr. Anst. Medd., Ser. Uppsatser 20.
S, W. R. G., and H. H. POOLE
3. The photo-electric measurement of the penetration of light of various wave-lengths into the sea and the physiological bearing of the results. Phil. Trans. Roy. Soc. B 222, p. 129.
6. The photo-electrical measurement of the diurnal and seasonal variations in daylight and a globe integrating photometer. Phil. Trans. Roy. Soc. London, Ser. A, 235, No 752.
0. A cubical photometer for studying the angular distribution of submarine daylight. Journ. Marine Biol. Assoc., v. XXIV.
S, W. R. G., H. H. POOLE, and F. J. WARREN
9. A balance-by-depth method for the photoelectric measurement of the vertical extinction coefficient of water. Journ. Marine Biol. Assoc., v. 28, p. 751.
EL, R.
1. Sur une nouvelle méthode de recherches qualitatives de la lumière dans les profondeurs différents de la mer. Bull. de l'Inst. Océanographique, No 219.
, E. A., and C. JUDAY
9. Penetration of solar radiation into lakes. Bull. Nat. Res. Nat. Acad. Washington.
INGTON, E. C., A. J. CARSOLA, and R. S. DIETZ
0. Oceanographic cruise to the Bering and Chukchi Seas, summer 1949. Part I: Sea floor studies. Navy electronics lab., Report no. 204.
NER, K.
8. Physikalische Bioklimatologie. Leipzig 1938.
NER, K., and E. SUTTER
2. Spektrale Empfindlichkeit und klimatische Verwendung der Kadmiumzelle. Strahlentherapie, Bd 45.

BÄCKSTRÖM, H. L. J.
1940. Über die UV-Absorption der Kobaltsalze und über einige Lichtfilter für das UV-Strahlengebiet. Arkiv för kemi, mineralogi och geologi, Bd 13 A.

CHANDRASEKHAR, S.
1950. Radiative Transfer. Oxford 1950.

CLARKE, G. L.
1933. Observations on the penetration of daylight into mid-Atlantic and coastal waters. Biol. Bull. v. 65, p. 317.
1936. Light penetration in the Western North Atlantic and its application to biological problems. Conseil Perm. Int. p. l'Explor. de la Mer, Rapp. et Proc. -Verb., v. CI, 2.
1938. Light penetration in the Caribbean sea and in the Gulf of Mexico. Journ. Marine Research, v. I, No 2, p. 86.
1941. Observations on transparency in the Southwestern section of the North Atlantic Ocean. Journ. Marine Research, v. IV, No. 3, p. 221.

CLARKE, G. L., and H. R. JAMES
1939. Laboratory analyses of the selective absorption of light by sea water. Journ. Optical Soc. Amer., v. 29.

COOPER, L. H. N., and A. MILNE
1938. The ecology of the Tamar Estuary II. Underwater illumination. Journ. Marine Biol. Assoc. United Kingdom, v. 22, p. 509.

DARBY, H. H., E. R. F. JOHNSON, and G. W. BARNES
1937. Studies on the absorption and scattering of solar radiation in the sea; spectrographic and photometric measurement. Pap. Tortugas Lab., Carnegie Inst. of Washington, v. 31, p. 193.

DIETRICH, G.
1939. Die Absorption der Strahlung im reinen Wasser und im reinen Meerwasser, Ann. d. Hydrogr. u. mar. Meteor., Bd 67, p. 411—417.

ELLINGER, F.
1935. Sonderband der Strahlentherapie, 20.

GALL, H. M. W.
1949. Measurements to determine extinction coefficients in the North Sea and English Channel, Journ. Marine Biol. Assoc. United Kingdom, v. 28, p. 757.

GANS, R.
1928. Lichtzerstreung. Handb. d. Exp. Phys. BD XIX. Leipzig.

HULBURT, E. O.
1928. The penetration of ultraviolet light into pure water and sea water. Journ. Optical Soc. Amer., v. 17.

JAMES, H. R., and E. A. BIRGE
1938. A laboratory study of the absorption of light by lake waters. Trans. Wisconsin Acad., v. XXI.

JERLOV (JOHNSON), N. G.
1944. A standard transparency-meter. Svenska hydr.-biol. kommissionens skrifter. Ny serie XIX.
1946. On antirachitic ultra-violet radiation in the sea, Medd. fr. Oceanografiska Institutet, Göteborg. No 8.

JERLOV (JOHNSON), N. G., and G. LILJEQUIST
1938. On the angular distribution of submarine daylight and the total submarine illumination. Svenska hydr.-biol. kommissionens skrifter. Ny serie Hydrografi XIV.

JERLOV (JOHNSON), N. G., and H. OLSSON
1943. On the standardisation of photoelectric elements by means of solar radiation. The total energy of incident radiation computed from records with photo-electric elements. Geografiska Annaler, H 3—4.

JERLOV (JOHNSON), N. G., and B. KULLENBERG
1946. On radiant energy measurements in the sea. Svenska hydr.-biol. kommissionens skrifter. 3:e ser hydrografi, Bd 1, H. 1.

JERLOV (JOHNSON), N. G., and T. LEVRING
1946. The photosynthetical effect of ultra-violet radiation on some marine algae. Medd. fr. Oceanografiska Institutet, Göteborg, No 11.
1947. On the production of vitamin D in the sea. Svenska hydr.-biol. kommissionens skrifter. 3:e ser. hydrografi, Bd 1. H. 3.

JOSEPH, J.
1949. Durchsichtigkeitsmessungen im Meere im ultravioletten Spektralbereich. Deutsche Hydr. Zeitschr. Bd 2, H. 2. p. 212.
1949. Über die Messung des »Vertikalen Extinctionskoefficienten». Deutsche Hydr. Zeitschr. Bd 2, H. 6.
1950. Durchsichtigkeitsregistrierungen als ozeanographische Untersuchungsmethode. Deutsche Hydr. Zeitschr. Bd 3, H 1, p. 69.

KALLE, K.
1937. Meereskundliche chemische Untersuchungen mit Hilfe des Zeisschen Pulfrich Photometers. Ann. d. Hydr. u. mar. Meteor. H VI.
1938. Zum Probleme der Meereswasserfarbe. Ann. d. Hydr. u. mar. Meteor. 66. H 1.
1939. Die Farbe des Meeres. Conseil Perm. int.p. l'Explor. de la Mer, Rapp. et Proc.-Verb., v. CIX.

KNUDSEN, M.
1922. On measurement of the penetration of light into the sea. Conseil Perm. Int. p. l'Explor. de la Mer, Publ. de Circonstance, No 76.

KRÜMMEL, O.
1907. Handbuch der Ozeanographie. Stuttgart
LE GRAND, Y.
1939. La pénetration de la lumière dans la Annales de l'Inst. Océanographique, XIX, p 393.

LILJEQUIST, G.
1940. The thalassological cruise in July 1939. Pl metric observations. Havsforskningsinstit skrifter no 127, Helsingfors.

MERKER, E.
1931. Die Fluoreszenz und die Lichtdurchlässi der bewohnten Gewässer. Zool. Jahrb. (Physiol.).

MEYER, A. E. H., and E. O. SEITZ
1942. Ultraviolette Strahlen. Berlin 1942.

ORTH, R.
1939. Zur Kenntnis der Lichtklimas der Tropen Subtropen sowie des tropischen Urwa Gerlands Beiträge zur Geophysik, Bd 55,

OSTER, R. H., and G. H. CLARKE
1935. The penetration of the sea, green and comp. of daylight into atlantic waters. J Optical Soc. Amer., v. 25, p. 611.

PETTERSSON, H.
1934. Scattering and extinction of light in sea-w Journ. Optical Soc. Amer., v. 4.
1934. A transparency-meter for sea-water. Medd Oceanografiska Institutet, Göteborg, N
1936 a. Das Licht im Meer. Bioklim. Beiblätter,
1936 b. The transparency of sea-water. Conseil I Int. p. l'Explor. de la Mer, Rapp. et Proc.-V v. 101, 2.

PETTERSSON, H., and S. LANDBERG
1934. Submarine daylight. Medd. fr. Oceanogra Institutionen, Göteborg, no 10.

PETTERSSON, H., and H. H. POOLE
1937. Measurements of submarine daylight. M fr. Oceanografiska Institutionen, Göteborg, n

POOLE, H. H.
1936. The photo-electrical measurement of subm illumination in offshore waters. Conseil I Int. p. l'Explor. de la Mer, Rapp. et Proc-V v. 101, pt 2, no 2.
1945. The angular distribution of submarine day in deep water. Scient. Proc. Roy. Dublin v 24, no 4.

POOLE, H. H., and W. R. G. ATKINS
1926. On the penetration of light into seawater. J Marine Biol. Assoc. v. 14. p. 177.
1929. Photo-electric measurements of submarine mination throughout the year. Journ. M Biol. Assoc. United Kingdom, v. 16, pp 324.
1937. The penetration into the sea of light. Proc. Soc. London, v. 123. p. 151.

POWELL, W. M., and G. L. CLARKE
1936. The reflection and absorption of daylight surface of the ocean. Journ. Optical Soc. A v. 26, p 111.

REGNARD, P.
1891. Recherches expérim. sur les cond. phys. vie dans les eaux. Paris 1891.

, G. A., H. Stommel, and D. F. Bumpus
). Quantitative ecology of the plankton of the Western North Atlantic. Bull. Bingham Oceanogr. Coll., v. XII, 3.
RER, F.,
3. Zur Methodik der Durchsichtigkeitsmessung im Wasser und deren Anwendung in der Limnologie. Archiv f. Hydr., 33.
RER, F., and F. Ruttner
. Die Strahlungsverhältnisse der Binnengewässer. Leipzig 1941.
:R, W. R.
. The spectr. absorption of light by pure water and Bay of Fundy water. Contr. to Canadian Biology and Fishery., v. 7.
r, G.,
5. Geographie des Atlantischen Ozeans. Hamburg 1926.
E. O.
3. Filter und Filterkombinationen für Strahlungsmessungen mit Photo-zelle im UV-Spektralgebiet. Strahlentherapie, Bd 48.
ORD, V. E.
). Die Messung des Eindringens des Lichtes in Wasser mit photoelektrischen Zellen. In: Aberhalden: Handb. d. biol. Arbeitsmeth. IX, II/2.
ORD, V. E., and F. W. Gail
2. A study of light-penetration into seawater made with the Kunz photoelectric cell with particular references to the distribution of plants. Publ. Puget Sound. Biol. Stat. 3.
Mou-Tsao
). Untersuchung über die Eignung der Selenphotoelemente zur UV Dosimetrie. Dissert. Berlin 1939.
CHOWSKI, M. v.
3. Molekular-kinetische Theorie der Opalezens von Gasen im kritischen Zustande sowie einiger verwandter Erscheinungen. Ann. d. Physik (4) 25, pp 205—226.
RUP, H. U., M. W. Johnson, and R. H. Fleming
2. The Oceans their physics, chemistry, and general biology. New York 1942.
OUTI, Y.
5. Solar radiation in lake waters. Bull. Japanese Soc. Scient. Fish., v. 5, no. 3, p. 149.
MOTO, M. K.
3. Comparison entre l'absorption par l'eau et celle par le quartz dans l'UV lointain. Revue Opt., v. 7, p. 89.
BACK, C. L.
5. Spectr. bands of submarine solar radiation in the north Pacific. Conseil Perm. Int. p. l'Explor. de la Mer, Rapp. et Proc.-Verb., v. CI, 2.

Utterback, C. L., and T. W. Boyle
1933. Light penetration in the waters of San Juan Archipelago. Journ. Optical Soc. Amer., v. 23, p. 1.

Utterback, C. L., and P. M. Higgs
1938. A submarine photometer for studying the distribution of daylight in the sea. Journ. Optical Soc. Amer., v. 28, p. 100.

Vercelli, F.
1937. La propagazione delle radiazioni solare nelle acque marine. La Laguna di Venezia, v. 1. parte II, tomo V, p. 102.
1939. Misure subacque di radiazione in alcuni laghi alpini. Boll. di Pesca, Pisc. e Idrob. 17.

Wattenberg, H.
1937. Die chemischen Arbeiten auf der »Meteor»-Fahrt Februar bis Mai 1937. Ann. d. Hydrogr., v. 65.
1938. Untersuchungen über Durchsichtigkeit und Farbe des Seewassers I. Kieler Meeresforschung, Bd II.

Whitney, L. V.
1938 a. Contin. solar rad. measurements in Wisconsin lakes.
1938 b. Transmission of solar energy and the scattering prod. by susp. in lake waters.
1938 c. Microstratification of inland lakes. Trans. Wisconsin Acad. v. 31.
1941. The angular distribution of characteristic diffuse light in natural waters. Journ. Marine Research, v. IV, p. 122.

Williams, M.
1929. Horizontal and upwards intensity of light in Puget Sound Waters. Publ. Puget Sound Biol. Stat. v. 7, p. 129.

Wright, W. D.
1944. The measurement of colour. London.

Wyrtki, K.
1950. Über die Beziehungen zwischen Trübung und ozeanographischem Aufbau. Kieler Meeresforschung Bd VII, 2, p. 87.

Young, R. T. Jr.
1939. Measurements on the transparency of sea water off the coast of Southern California. Journ. Marine Research, v. II, p. 117.
1943. A note on some laboratory measurements of the transparency of sea water. Journ. Marine Research, v. V, 2, p. 111.

Young, R. T. Jr., and R. D. Gordon
1939. Report on the penetration of light in the Pacific Ocean off the coast of southern California. Scripps Inst. Oceanography, Univ. Calif., Bull., Techn. ser., v. 4, p 197—218.